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ON DOPPLER'S PRINCIPLE, IN CONNECTION WITH THE STUDY OF THE RADIAL VELOCITIES ON THE SUN¹

By A. COTTON

It is by means of the spectroscope, as is well known, and in making use of the Doppler principle, that astronomers are enabled to determine radial velocities. I was led to make some remarks on this subject at the meeting of the International Union for Co-operation in Solar Research, in September, 1910, at Mount Wilson, and I am desirous of publishing them here, together with some additional statements. They apply to the case where the source of light of which the displacements are to be determined is a star surrounded, as is the sun, by an atmosphere.

It seems to me that sufficient attention has not been given to the paper by W. Michelson, of Moscow, published in this Journal (13, 192, 1901), "On Doppler's Principle," where the author points out that the relative motion of the source and of the observer is not the only cause which could produce a change of wave-length in the spectral lines. If the observer is at rest and the source stationary, but if the thickness or index of a refracting medium intervening between them is rapidly changed as the light passes through it, the spectrum will be changed. The time that it takes the light to travel from the source to the observer depends, in fact, not on the simple geometrical thickness of the media passed through, but upon

¹ Translated from author's proofs of an article appearing in *Le Radium*.

their *optical* thickness (product of the thickness by the index of the medium for the light which passes). If the index of this medium is changed (for instance, if it is a gas, by compressing it), or its thickness, the luminous vibrations will not reach the observer separated by the same interval of time as if the medium remained constant, and the spectral lines will be slightly displaced while this medium varies.

The small variation $d\lambda$ of the wave-length λ (in a vacuum) of a given monochromatic ray is easily computed if the variations at each instant of the total *optical length* of the path traveled are known. This total optical length L is the sum of a series of terms $n_1 l_1, n_2 l_2, n_3 l_3, \dots$ where l_1, l_2, l_3, \dots are the paths traveled in the different media, n_1, n_2, n_3, \dots being their indices (referred to a vacuum),

$$L = n_1 l_1 + n_2 l_2 + n_3 l_3 + \dots = \Sigma n l.$$

If we let dL/dt represent the derivative of this expression with respect to the time, we have the following general formula for the Doppler-Fizeau effect,

$$\frac{d\lambda}{\lambda} = \frac{1}{V} \cdot \frac{dL}{dt},$$

where V is the velocity of the light in a vacuum.

If the light everywhere passes through a vacuum, we find that the formula usually employed in practice for the computation of this effect, dl/dt , reduces then to the velocity v of the relative motion of the source and of the observer. Otherwise, it is necessary to consider the different terms of the sum; then we have the expression given by Michelson

$$\frac{d\lambda}{\lambda} = \frac{1}{V} \Sigma \left(l \frac{dn}{dt} + n \frac{dl}{dt} \right).$$

To be specific, I will discuss the two following simple cases where the distances l vary.

First case.—The source S and the observer O are separated by a constant distance D , but rays from S pass first through a thickness e of a uniformly refracting atmosphere of index n surrounding the source. Let us assume that this atmosphere is bounded by a

transparent screen perpendicular to SO . This limiting screen is displaced parallel to itself, along SO , with a velocity de/dt . We find, therefore,

$$V \frac{d\lambda}{\lambda} = \frac{d}{dt}(ne + D - e) = (n-1) \frac{de}{dt}.$$

Second case.—In this case, the observer O is again at rest, but the source S moves through the *motionless* atmosphere. Let de/dt be the velocity of the source. Then,

$$V \frac{d\lambda}{\lambda} = n' \frac{de}{dt},$$

where n' is the index of the atmosphere for the light which passes through it, already affected by the motion of the source, while in the preceding case n was the initial index. If the medium is dispersive, these two indices are not precisely identical: in fact, they will differ generally very little, but we shall see that this is not always the case, and for this reason I have designated them by different symbols.

Applications.—W. Michelson himself observed that the foregoing statement was applicable to various astronomical phenomena, particularly to certain peculiarities presented by the sun. He refers indeed to the abnormal displacements, very large in some cases, observed for certain lines near spots and prominences. The observers who discovered them, and who sought to explain them solely by the motion of the gases producing these lines, were led sometimes to admit enormous velocities—as great as 500 km per second. W. Michelson remarks that we need not assume in all cases these velocities which he considers exaggerated. It appears to him more plausible that these changes are due, for a considerable part at least, to motions in the non-luminous gases of higher level through which the rays pass in succession. Such motions, even directed almost perpendicularly to the rays, can in fact modify rapidly the optical path.

I will add that in these gaseous masses through which the rays pass there can be produced not only motions, but physical changes, notably condensations, accompanying the motions themselves. If, for example, a mass of vapors cools and passes to the state of

small liquid drops, or even fine solid particles (of which the influence on the propagation of light may be neglected), the rays which pass through it ought to have their wave-lengths displaced toward the violet. The inverse would be the result in the case of volatilization. If we consider the vast distances traversed we can conceive how such phenomena can persist, without appreciable changes, throughout the duration of the observations.

Case of the solar rotation.—W. Michelson considers in his memoir only those accidental phenomena observed in studying the sun; the question may be raised whether the same considerations ought not to be involved in the spectroscopic investigation of the regular rotational motion of the sun itself. It is evident indeed that *rigorously* this influence of the variations in the optical path ought to alter, first, the law of distribution of radial velocities with the distance to the center, and then the manner in which the displacements estimated for the lines change with the wave-length.

To seek to estimate exactly what these alterations are is really impossible, for it presupposes data about the solar atmosphere which we do not possess. The rigorous solution would involve, in addition, the consideration of the impulse given the waves by a medium in motion. But it is possible to gain at least an idea of the way in which they operate in the purely theoretical case of a sphere *S* surrounded by a homogeneous atmosphere which rotates with it and is limited, for example, by a thin transparent envelope.

We will assume that this rotating sphere has on its surface a point emitting a monochromatic¹ radiation, and that we follow with the spectroscope the corresponding line, moving the spectroscope as the sphere rotates. In reality, the observations are made differently: we compare the positions of lines corresponding to different points of the solar image, that is, at any point on the sun which we are observing the luminous sources are renewed at each instant. But, as the light emitted by each of these sources behaves as that of a luminous point considered separately, and as the variations of the optical path affect it in the same way, the comparison is legitimate.

¹ This sphere *S* will correspond then to the periphery, compared to a definite surface, of the reversing layer beginning with which the spectrum of the emitted light contains the dark-line standards.

To simplify this problem further, let us assume provisionally that the index n is not altered by the motion, and draw Fig. 1, neglecting the refractions on leaving the assumed atmosphere. It is thus possible to compute, for each position of the point under examination, the value of the optical path and the corresponding expression of the Doppler-Fizeau effect. Omitting the details of the solution of this problem, I indicate only this result: the Doppler-Fizeau effect is greater,¹ and increases a little more rapidly with the distance from the center, than if there were no atmosphere.

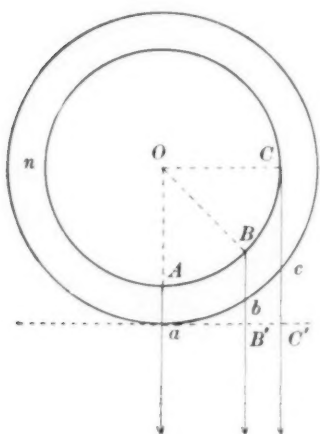


FIG. 1

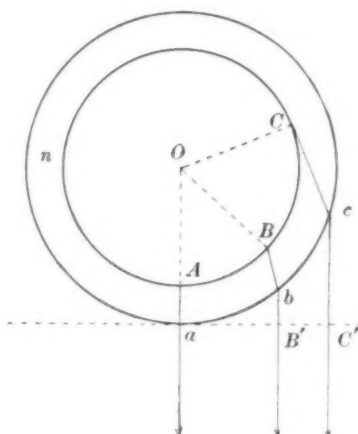


FIG. 2

At the edge of the image it is equal to n times the value it would have if there were no atmosphere. If the index differs only slightly from 1, the correction due to the atmosphere would be insignificant.

We have neglected the refractions. We could consider them in the case theoretically assumed: it is possible indeed, if not analytically, at least graphically, to seek to find how the optical path varies, as a function of the time, or, what amounts to the same thing, the value of $nBb + bB'$ (Fig. 2). But in reality, the atmosphere not being homogeneous, and the index of refraction decreasing on passing from the sphere S , the actual problem will be more complicated. Suffice it to say that we can expect to find for certain regions of the solar image, where the curvilinear part of the course

¹ I assume here the index greater than 1.

has great relative importance, a Doppler effect greater than that computed above without considering the refractions.

If the refractions enter and play an important rôle, as Julius in particular has assumed, we would see with respect to the sun a veritable anamorphosis, a deformed image, especially near the limbs, where we would see points which without refraction would be invisible from the earth. The rotation period—assuming that it could be determined with precision (if there were, for example, a standard, such as a spot, sufficiently well defined)—would vary with its distance from the solar equator; and would vary even with the wave-length, if the atmosphere is dispersive.

We do not actually know whether these refractions exist and play an appreciable rôle. If they do exist, there results from them, from the point of view of the Doppler effect, a first consequence, pointed out recently by M. Perot,¹ which is found from a purely geometrical point of view: M. Perot remarks that the direction of the ray having changed between the point of departure of its curved path and the rectilinear part which it then follows to reach the earth, the Doppler effect gives us the component of the velocity of the sun according to the direction of the luminous ray *near the source*. But this is not all: we must take into account also the progressive alterations which the vibratory periods undergo *later* by reason of the continual variation in the optical path. There is no decisive reason, it seems to me, for neglecting this second effect. To admit that the rays deviate notably from propagation in a straight line is to admit that the values of the indices differ from 1 by appreciable amounts; it is accordingly necessary to take into account the effect which the refracting media passed through have *themselves* produced on the observed wave-length. This will contribute to a modification of the laws of the Doppler effect; for this further reason (granted that the indices are not the same for the different colors) the changes undergone by lines of the same origin will no longer vary proportionally to the length of the initial wave.

The question accordingly is: Do the indices differ appreciably from unity? At this point intervenes the anomalous dispersion

¹ *Comptes Rendus*, 151, 848, 1910.

on which Julius has insisted, first in pointing out that it could increase the assumed refractions, and more recently¹ in endeavoring to show that *diffusion* can intervene, which could widen the lines in an unsymmetrical fashion.

Many astronomers feel that, at least in the first form that he gave to his theory, Julius exaggerated the importance of the rôle played by the anomalous dispersion; it is not less true that this rôle ought to be examined a priori, since the rays from the sun pass through some media in which there are at least some of the gases of the layer which causes the reversal of the lines. As soon as the dispersion of these media becomes anomalous in the region of certain Fraunhofer lines, then we may inquire whether this anomalous dispersion intervenes in the Doppler effect itself.

Doppler effect and anomalous dispersion.—It will be recalled that the anomalous dispersion of the gases in the different cases studied always presents the same characteristics, namely, those studied in the region of the D-lines by Henri Becquerel. We are led to liken the curve of dispersion in the region of the line to the two branches of a hyperbola having one asymptote parallel to the n -axis. On the red side of the maximum of absorption the curve rises rapidly, on the violet side it falls, as shown in Fig. 3, where it has been assumed, for simplicity, that the index, at a distance from the line on either side, was equal to 1. Observations have up to this time been impossible in the central region

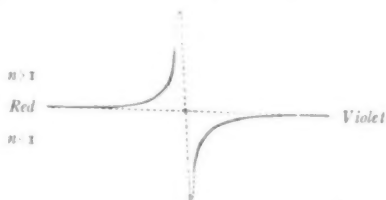


FIG. 3.

of the line. It seems to me that it would be difficult to assume infinite and *negative* values for the index, and I would more willingly believe that the curve resembles, in the narrow portion heretofore unknown, the curve for liquids or absorbing solids, i.e., that between a maximum and minimum value the index returns to normal values. But from our point of view, it is sufficient to admit what is an observed fact, namely, that if the center of the line is approached closely enough from the red we find large values

¹ *Le Radium*, 7, 281, 1910.

for the index, and that the reverse is true when we enter the ray from the violet side.

We can accordingly return to the two simple cases, where we deal with a simple motion of recession of a limiting surface or of the source, which I discussed at the beginning. Both are interesting in that they correspond to possible experiments,¹ but I will discuss only the second, because it seems to correspond to an experiment that has been made.

Let us suppose that the source emits a ray, that the surrounding gas at rest absorbs this line and introduces the anomalous dispersion. If the source moves toward the observer, the index n' , which occurs in the formula given above,

$$\frac{d\lambda}{\lambda} = n' \frac{v}{V},$$

corresponds to an apparent period shorter than the initial period; it is accordingly sensibly less than 1. The Doppler effect will accordingly be diminished by the presence of the absorbing medium proportionally, up to a certain limit at least, as the value of the velocity will be less. Contrariwise, if the source recedes from the observer with the same velocity, the index not being notably more than 1, the Doppler effect is increased.

It is precisely in this way that Dufour,² who has drawn attention to this intervention of the anomalous dispersion, explains the observations which he has made in rotating a mercury-arc suitably arranged in a magnetic field which makes it turn very rapidly. The displacement of the lines (or rather of the fringes) obtained is about twice as great when the side of the arc which recedes from the observer is studied: this is what Dufour is considering when he assumes that the moving portion of the arc is surrounded by an absorbing layer at rest.

It would be well to be assured that the mercury vapor indeed

¹ The first case could be realized by an experiment analogous to that of Belopolsky. Belopolsky was the first to seek to demonstrate the Doppler effect by an optical experiment in a laboratory: he varied rapidly by reflections the path in air between the source and the observer (see this Journal, 13, 15, 1901). The air might be replaced, for the variable portion of the course, by a refracting medium.

² *Comptes Rendus*, 151, 62, 1910.

exhibits anomalous dispersion in the region of the spectrum under discussion; to determine also whether such a dissymmetry in the Doppler effect, and an influence analogous to anomalous dispersion, do not enter into the experiments recently made on the Doppler effect in the case of canal rays or anode rays.

In short, we may say that the *rapid and irregular* motions of a source in the midst of an atmosphere, with regard to anomalous dispersion, ought to cause a displacement *toward the red* of the "center of gravity" of the corresponding line transmitted by this atmosphere. We might even be tempted to explain, on this basis, by the molecular motions themselves, the displacement of the lines toward the red, produced by an increase of pressure, which Humphreys has discovered. This displacement has quite the characteristics of a dissymmetrical broadening; it is accomplished quite as would be expected, but it is difficult thus to interpret the fact that it is the *total* pressure which is taken into account and not the pressure of the gas solely which gives the lines studied.

If we pass now to the case of the solar rotation, discussing the possible influence of the anomalous dispersion, we find that the problem is more complicated, because rigorously it is not legitimate to make the foregoing assumption, namely, that the index is not altered by the motion of the atmosphere. Without doubt the atmosphere is drawn along by the rotational motion, but even if there is not a relative sliding of the superposed layers, the effect is not exactly the same as if there were a simple motion of translation: the velocities at different points are not the same, and their components with respect to the ray are different. When a ray which the observer will receive later passes a point *M* of the atmosphere, this point *M* receives vibrations which no longer have the initial period, but an apparent period which differs from it.¹ But

¹ It should be added that to treat the problem completely it would be necessary to take into account the Fizeau effect (impulse of the waves) which occurs when the medium where the light is propagated is in motion with respect to the source. The velocity of the waves (Lord Rayleigh, Gouy) in a medium which moves with a velocity of which the component perpendicular to the waves is v is given (see Drude, *Lehrbuch der Optik* [1st ed.], p. 427; or Wood, *Physical Optics*, p. 526) by the equation

$$\omega' = \frac{V}{n} + v \left(\frac{n^2 - 1}{n^2} - \frac{\lambda}{n} \frac{dn}{d\lambda} \right).$$

in the medium assumed a very small variation of period may produce a considerable change in the index.

I do not believe, in view of these considerations, that it would be useful to take up again even the theoretical problems indicated above, and to investigate a priori whether one can expect effects of which the order of magnitude should be acceptable.

It is more interesting, it seems to me, to note that there is an experimental way of determining whether the anomalous dispersion intervenes, in a general way, in astronomical observations; of learning whether it explains certain paradoxical facts ascertained sometimes in the study of radial velocities.¹

This would consist of systematically determining whether these established anomalies are observed precisely on the lines near which the anomalous dispersion is the most evident. The researches (still much too few) on anomalous dispersion show, in fact, that its influence is not equally distinct in the vicinity of different lines of the same body; it is thus that Ladenburg and Loria² have succeeded in demonstrating it clearly for hydrogen near the red line, but they have not been able under the same conditions to establish it definitely in the region of the blue line. Here also the comparison of astronomical observations with researches in the laboratory will be fruitful.

LABORATOIRE DE PHYSIQUE
ÉCOLE NORMALE SUPÉRIEURE
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¹ Different lines, even of the same origin, lead to different computed velocities.

² *Berichte der deutschen physikalischen Gesellschaft*, **10**, 858, 1908.

ON THE MAGNETIC SEPARATION OF THE SPECTRAL LINES OF CALCIUM AND STRONTIUM

By B. E. MOORE

I. INTRODUCTION AND METHOD

A few of the lines of these substances have been investigated by Runge and Paschen.¹ William Miller² has studied a few more of the lines.

The method and notation³ are the same as used by these experimenters and by myself in previous contributions.⁴ The grating has been kindly loaned by Professor Hale of Mount Wilson Solar Observatory. It is a concave grating of 21 feet focal length and 14,438 lines to the inch. The camera is of the circular type. The field-strength varied from 28,000 to 31,000 gauss. All measurements have been reduced to 24,450 gauss to compare with my previous measurements. The field-strength was estimated from the separation of lines recorded by Runge and Paschen. These strong lines occurred as reversals upon my plates when the salt was introduced into the spark. They were of the usual type, when they came from the impurities present in the carbon electrodes. Calcium is more prominent in the carbon than strontium. Consequently there were more good lines to determine the field-strength with the strontium plates than with the calcium. The *p*- and *s*-components were separated by calcite and photographed at different times. Consequently there has been no attempt to obtain the relative intensities of the *p*- and *s*-components.

In order to make this investigation more complete than previous experiments, it has been necessary to take photograms varying

¹ *Astrophysical Journal*, **16**, 123, 1902.

² *Annalen der Physik*, **24**, 105, 1907.

³ The components of the vibrations parallel to the lines of force are designated by *p*- and those perpendicular to the lines of force by *s*-. Wave-lengths are designated by λ ; and change of wave-frequency per centimeter with a field-intensity of 24,450 gauss is represented by $\frac{\Delta\lambda}{\lambda^2}$. Intensity of components, when recorded, is designated by *i*.

⁴ *Astrophysical Journal*, **28**, 8, 1908, and **30**, 143, 1909.

in time of exposure from 15 minutes to 10 hours. For these long exposures it was necessary to maintain the grating room at constant temperature and to insure the grating and carriage from any sudden shock. This could be done satisfactorily only at night. Fortunately the required field-strength could be obtained with the magnet excited with as small a current as six amperes, which permitted running the magnet continuously without excessive heating.

II. OBSERVATIONS AND RESULTS UPON CALCIUM

Table I contains some representatives of the first subordinate series. Miller designates 4956.1 as a quadruplet. The character of the *p*-component cannot be distinguished upon my plates. There are at least two *p*-components, and it is safe to call it quadruplex.

TABLE I

λ	$\frac{\Delta\lambda}{\lambda^2}$		λ	$\frac{\Delta\lambda}{\lambda^2}$	Remarks
	Moore	Miller			
4956.8	± 1.27	....	....	....	Satellite
56.1	1.29s	....	3644.9	....	Satellite
55.0	1.29	± 1.24	44.5	± 1.24	Principal line
4435.0	-1.40s +0.78s	1.13s 1.03p	3631.1	....	Satellite
35.1	1.14	1.06	30.8	1.10	Principal line
34.12	1.11				Satellite
4425.6	0.70	0.57	3624.1	(0.60)	Principal line
24.83	1.13	....	....	....	Satellite

Its companion line 3644.9 has only one weak red component visible; the blue components are doubtless lost in 3644.5. It is, therefore, presumably quadruplex also. The next pair, 4455.0 and 3644.5, are duplicates. Line 4435.9 has a red *s*-component of intensity 5 and a blue *s*-component of intensity 10. I think this line is unsymmetrical, having the *s* (red) separation twice the magnitude of the *s* (blue). Measured symmetrically it agrees well with Miller's value. The same difficulty is met with the *p*-components of this line as with 4956.1. Line 3631.1 is the hypothetical duplicate of 4435.9. It has both its *p*- and *s*-blue components lost in 3630.8, and its red components are weak and diffuse. The

position of the components makes the line at least a quadruplet. The next pair, 4435.1 and 3630.8, are the same. 4435.1 has a blue satellite 4434.12, which I have not been able to trace to an impurity. Lines 4425.6 and 3624.1 are probably duplicates. It is difficult to get sharp measurements for these close pairs. Line 4425.6 has also a blue satellite 4424.83.

In the second subordinate series of triplets, Kayser and Runge give six terms. Only the first two terms are well defined upon my plates, the third term is weak and the remainder are not present. The lines and their separations are given in Table II. The corresponding members of the two terms are plainly duplicates. For the quadruplet pair s - equals $3p$ -.

TABLE II

λ	$\frac{\Delta\lambda}{\lambda^2}$	λ	$\frac{\Delta\lambda}{\lambda^2}$
6162.5	± 1.34	3973.9	± 1.34
22.5	1.828	57.2	1.788
	.606	.....	(0.576)
03.0	2.00	49.1	2.08

TABLE III

λ	λ	λ	λ	λ
4586.12	4098.82	3876.2	3754.2	3678.5
81.66	5.25	2.9	50.9	5.5
78.82	2.93	0.9	49.0	4.4

Fowler gives another triplet series as recorded in Table III. The first three terms of this series were noticed by Kayser and Runge. Only the first two terms are well enough defined upon my plates for reasonable determination. The third term is confused by the presence of the carbon band lines. The fourth term is very weak, and although it looks like the first two terms, it needs a much stronger exposure. This series of lines is altogether abnormal in behavior. The lines are uniformly broad upon s -, p -, and "no field" plates. They are diffused over a space as wide as the normal triplet. If these lines were sharp, a separation of one-third normal could readily be measured. It was thought that

the widening of the lines (a method originally adopted by Zeeman and more recently by Hale in sun-spot study) might be taken as evidence of small separation. However, photographs of the "no field" lines of the same intensity as the *s*- and *p*-components showed no appreciable difference in their width. Line 4586.12 was the only exception in the six cases. It seemed somewhat wider on the *s*-plates. From this evidence I am disposed to say that in these lines we have series which show no Zeeman effect, although the possibility of a small separation must be conceded.

Table IV contains all the quadruplets observed outside of the principal series and those above recorded. These four lines con-

TABLE IV

λ	i	$\frac{\Delta\lambda}{\lambda^2}$
6499.9	2	$1.04s = 10 \times 0.104$
	1	$0.84p = 8$
94.0	10	$0.93s = 9$
	5	$0.73p = 7$
5264.4	8	$2.03s = 20$
	3	$1.03p = 10$
61.6	2	$1.48s = 14$
	1+	$1.27p = 12$

sist of two close pairs. They are all different but are all related. The separations can all be represented by multiples of a small factor, 0.104. This small factor has in numerous cases been found to be an aliquot part of a separation designated as normal. The normal value, "*a*," for the present field-strength is 1.105. The value 0.104 lies between $a/11$ and $a/10$, and too far from either of these values to be accepted as a rational part of the normal, or to state that the separations are multiples of that rational part.

Table V contains a list of the triplets measured. Generally the intensity of the *p*-component is about twice that of the *s*-pair of components. The intensities of the *s*-components are the only ones recorded. With reference to the Zeeman effect, the group of six lines between 4318.8 and 4283.2 is one of the most prominent of the calcium spectrum. The lines have nearly the same intensity and they differ but little in sharpness. The *p*-components are only one-third to one-half stronger than the *s*-components. But

the most prominent feature is the separation itself, which is the same for all of the lines. The separation seems also related to the normal, "a," and is one-half larger. No other magnitudes of separation in the triplet list are conspicuous.

TABLE V

λ	i	$\frac{\Delta\lambda}{\lambda^2}$	λ	i	$\frac{\Delta\lambda}{\lambda^2}$
6713.0	1	± 0.90	5270.5	15	1.24
471.9	3	1.24	262.5 [†]	5	...
62.8	15	1.05	189.0	2	1.08
50.0	3	1.08	041.9	1	(0.92)
39.4	20	1.10	4878.3	2	0.90
6160.9*	...	...	318.8	12	1.66
0.4*	...	...	307.9	12	1.65
5857.8	10	1.03	302.7	15	1.66
603.0	3	2.05	290.1	12	1.66
1.5	5	1.67	89.5	12	1.65
5598.7 [†]	...	0.78	83.2	15	1.66
94.7	15	1.10	3961.2 [§]	1+	(1.10)
90.3	4	(1.87)			
89.0	20	1.43			
82.2	8	1.50			

* These lines overlap. Separation is large.

[†] Unsymmetrical in intensity and probably also in separation. Red intensity 8, blue intensity 12.

[‡] Has very narrow separation.

[§] Possibly aluminum line 3961.7.

III. OBSERVATIONS AND RESULTS UPON STRONTIUM

Table VI contains the lines studied belonging to the second subordinate series of triplets. Three more terms of this triplet series are known, but they do not appear upon my plates. It is at once seen that the pairs in these two terms agree. The middle pair is a magnetic quadruplet whose separations are in the ratio of 4 to 1.

TABLE VI

λ	$\frac{\Delta\lambda}{\lambda^2}$	λ	$\frac{\Delta\lambda}{\lambda^2}$
7070.7	± 1.50	4438.22	± 1.48
6878.8	1.908	361.87	1.958
	0.50 ρ	...	0.48 ρ
6791.4	2.22	326.60	2.10

Table VII contains all the observable lines belonging to the first subordinate series. There are three strong lines in each term

called principal lines. These are accompanied by weaker lines designated satellites. In all there are six and possibly seven members in each term. The first principal line is the only one which can be measured for three terms, and in the third case it is probably overlapped by its first satellite (3706.2). These three representatives agree. The satellites 4968.11 and 4032.51 agree in their *s*-components. It is difficult to tell the real character of the *p*-components. The *p*-plates show that both lines are either unsymmetrical in magnetic separation, or that each line is a close natural doublet. If they are unsymmetrical in separation, one component

TABLE VII

λ	$\frac{\Delta\lambda}{\lambda^2}$	λ	$\frac{\Delta\lambda}{\lambda^2}$	λ	$\frac{\Delta\lambda}{\lambda^2}$	Remarks
4071.85	± 2.73	4033.25	.....	.....	.....	Satellite
68.11	1.638	2.51	± 1.588	.....	.....	Satellite
	0.81 <i>p</i>	.....	..... <i>p</i>	.....	.....
62.45	1.29	0.45	1.30	3705.88	± 1.29	Principal line
4876.35	1.61	3970.15	.....	.....	.....	Satellite
2.66	1.03	69.42	(1.59?)	.....	.....	Principal line
4832.23	1.65	3940.88	0.00?	.....	.....	Principal line
0.15	0.49	.....	.....	.....	.....	Satellite

is about three times as far removed from the zero position as the other; and the total separation equals the value for the *s*-components. For line 4968.11 the blue *p*-component is three times as bright as the red and one-third as far from the "no field" line. For the companion line, 4032.51, the phenomena are reversed. The appearance of the "no field" line favors regarding these lines as opposite and equal dissymmetries. If the first line has really a close blue companion, then the second one must have a close red companion. These two weaker lines would have equal *p*-doublets. But if this be true, it is difficult to reconcile the small displacement upon the "no field" plate relative to the stronger *p*-component. Line 3970.15 is a diffuse triplet and too weak to measure. It may be identical in separation with its companion 4876.35. These lines are not alike, however, in general appearance. Line 3969.42 is broad and diffuse, and only the red component is visible. The

blue component is overlapped by the strong calcium line 3968.63, which occurs as an impurity in the electrodes. However, the separation is roughly the same as 4876.35 and not the same as the line 4872.66, which precedes it in the series. Line 4832.23 is the first representative of the third principal series. Its separation is three halves times the normal triplet and identical with the first line of the second series. Line 4832.23 is further characterized by having a satellite upon its more refrangible side whose wavelength is 4832.15. This line was first noted by Miller, and its components lie entirely within those of the principal line. The next line in the series with 4832.23 is 3940.88. Its peculiar diffuseness suggests a small separation, together with the presence of an overlapping line, as if there were a close satellite present as in line 4832.23. However, the separation here, if there be any separation at all, must be much smaller than obtained for 4832.23. So far as these series have been studied, then, it is seen that Preston's law is confirmed only in the first three terms of the first principal line.

Table VIII contains the separations of three series of lines given by Fowler. It is apparent that there is no uniformity in the

TABLE VIII

SERIES 1		SERIES 2		SERIES 3	
λ	$\frac{\Delta\lambda}{\lambda^2}$	λ	$\frac{\Delta\lambda}{\lambda^2}$	λ	$\frac{\Delta\lambda}{\lambda^2}$
5535.01	± 1.66	5504.48	± 1.31	5486.37	2.04s
257.12	1.31	229.52	1.55s	.....	1.32s
4802.20	1.32	.....	0.61p	.....	0.70p
4338.05	0.00	4868.92	1.21	.....	0.00p
4087.67	.....	4319.39	0.00?	5213.23	.....
3950.96	.....	4071.01	.....	4855.27	1.41
		3935.33	.....	4308.49	0.00
				4061.21	.....
				3926.27	.....

separations of these lines in either of the three series. The separation 1.66, which is three halves times the normal, occurs four times, three times in triplets and once in a seven component line, but it occurs only twice in one series. There are no further duplications. These series are characterized by having a constant difference on

the scale of vibration between corresponding members. That is, between F_{11} (Fowler's series 1, line 1) and F_{21} , the frequency-difference is the same as between F_{12} and F_{22} . Designate this frequency-difference by $\nu_1 = 100$ (about) and the difference between F_{21} and F_{31} by $\nu_2 = 59$ (about). They are, then, similar to the principal lines in the two previous series of triplets. However, none of the types of separation, except 1.66, in these series occurs in the previous series. But there are some lines outside of the known series which agree in type with some of the lines in the Fowler series. The most prominent case is the seven component lines 5540.3 and 5486.4 (F_{31}). Each of these two lines has two other lines similarly situated with respect to each other on the scale of vibration frequency as shown in Table IX. However, in this new

TABLE IX

5540.3 F_{11} $\left\{ \begin{array}{l} l \\ 35.0 \end{array} \right\}$	17.4 = ν_1	5486.4 F_{31} $\left\{ \begin{array}{l} l \\ 81.1 \end{array} \right\}$	17.6 = ν_1
54.5 F_{21} $\left\{ \begin{array}{l} l \\ 100. \end{array} \right\}$	100. = ν_1	51.1 F_{31} $\left\{ \begin{array}{l} l \\ 100. \end{array} \right\}$	100. = ν_1

grouping, it is 5451.1 which is the magnetic duplicate of 5535.0 and not 5481.1. The value ν_3 corresponds closely to the distance of the first satellite from the first principal line in the first subordinate series. This value is repeated in the distance between the lines 5229.5 (F_{22}) and 5225.4. However, F_{22} has four instead of seven components; and 5225.4 duplicates neither 5535 nor 5481.1, but is probably a duplicate of 5522. Both 5225.4 and 5522 are unsymmetrical, and the total distance between their respective components is probably the same.

Fowler's series do not conform to Preston's law in any way whatsoever. Judged by the Zeeman effect, there are some lines not included in the series more intimately associated with some of the series lines than these series lines are with each other. It has not been possible to group either the lines which do agree into a series or to take the corresponding lines outside of the series and group them into other co-ordinate series.

Table X contains two quadruplets, the only ones which occur outside of the series already given. These separations are multiples of the same small value, 0.104, found for the four quadruplets in

calcium, Table IV. However, the multiples of this small value differ for all six lines. Therefore, although related, they are of different types.

TABLE X

λ	$\frac{\Delta\lambda}{\lambda^2}$
6041.4	$0.95s = 9 \times 0.104$
	$0.94p = 9 \times 0.104$
6547.0	$1.35p = 13 \times 0.104$
	$0.73p = 7 \times 0.104$

Table XI contains a list of all the triplets studied which are not already included in the series Tables VI to VIII. A few of the stronger lines have a separation of three halves times the normal "a." However, there is no defined tendency of the separations to cluster about any given magnitude.

TABLE XI

λ	i	$\frac{\Delta\lambda}{\lambda^2}$	λ	i	$\frac{\Delta\lambda}{\lambda^2}$
6550.5	8	± 1.12	4812.0	25	± 1.64
504.2*	10	1.14	784.4	15	1.71
466.2	1	(0.95)	70.6‡	2	(1.12)
46.2	1+	1.73	42.1	10	1.68
08.6	15	1.23	22.4	25	1.64
6300.7	1+	(1.16)	4678.4‡	2	(1.03)
86.8	1+	(1.41)	607.5§	..	1.10
80.9	2	1.53	531.5	8	1.46
5543.5	2	1.16	480.7¶	2	0.00
522.0	8	0.60	54.8¶	3	1.30
481.1	15	1.47	51.9¶	1+	0.87
451.1	10	1.65	12.9	5	1.72
330.0†	2	....	4031.9	1+	(1.50)
5238.8	8	1.09	3963.3	5	1.26
225.4	3	0.63	44.3	1+	(1.50)
156.4	2	1.47	3307.6	3	1.78

* p -component has the same intensity as the s -pair of components.

† Not identified, like 5522 and 5225.4.

‡ These two lines are alike in diffuseness.

§ Reversal.

¶ Lines not identified.

IV. COMPARISON OF CALCIUM AND STRONTIUM

The principal and second subordinate series of doublets show the same uniform separation both in magnitude of separation and in number of components in all substances in which the types have

been found. In calcium and strontium we have two other types of series called triplet series. However, in the first subordinate series the principal lines are accompanied by weak companions or satellites. From Preston's law we should expect not only that the lines in successive terms of the series should correspond, but also that there should be a similar agreement for the same series in passing from one substance to another. Now the first principal line in the first subordinate series in calcium is represented by separation (1.24) and 1.29, whereas the same series in strontium is represented by the values 1.29, 1.30, and 1.29; or the type is the same in the two substances. However, in the satellites there is no correspondence. In the second principal line the strontium representatives have separations in the ratio of three to two; and the separations of the calcium lines are 10 per cent larger than the smaller strontium value. The third principal line in calcium agrees in type with a close blue satellite of the third principal line of strontium. The remaining satellites neither agree in number of components nor in magnitude of separation. In the second subordinate series Preston's law is followed very well in either of the substances taken separately. But in passing from one substance to another the only similarity we find is that in each case we have two triplets and one quadruplet. The magnitudes of these separations are not comparable.

GENERAL CONCLUSION

The lines in the series sometimes follow Preston's law, but more frequently they fail to do so.

BRACE LABORATORY OF PHYSICS
LINCOLN, NEBRASKA
March 1911

ON THE RADIATION OF THE COMPANION OF *ALGOL*

By JOEL STEBBINS

In a previous study of the *Algol* system by the writer,¹ it was found that the form of the light-curve between minima is best explained by assuming that the companion keeps one side always toward the primary, and is brighter on that side, either because of reflection, or because of the heating effect of the radiation received from *Algol*. On page 212 of my article the reflection theory was dismissed as not sufficient to account for the observations. I am indebted to Father J. Stein of Amsterdam for calling my attention to a paper by Wilsing² on the reflection of the light of an *Algol* star by its companion, and the considerations in the present note have come from the correspondence between Father Stein and myself. We reached the agreement that while my reasoning in regard to the untenability of the reflection theory was insufficient, the main conclusion was correct. Although Wilsing's results are slightly in error, his method is perfectly suited to the case in hand, and from the importance of his formula it seems worth while to derive it anew. Pannekoek³ has already pointed out Wilsing's mistake, but he also has committed a trivial error in one numerical coefficient.

Let us proceed then with Wilsing and find, on the basis of Lambert's law, the amount of light reflected to the earth by the companion. Let the radius of *Algol* be taken as unity, and let J be the measure of the radiation emitted per unit surface of *Algol* in a direction perpendicular to the surface. Then the total radiation from the bright disk in the direction of the earth is given by

$$J_1 = \pi J. \quad (1)$$

Consider the companion to be at superior conjunction, and we have for the total radiation, J_2 , which the companion reflects toward the earth,

$$J_2 = \frac{\mu}{\pi} \iint \frac{J \cos \theta \cos \theta' \cos \phi \, ds \, ds'}{\rho^2} \quad (2)$$

¹ *Astrophysical Journal*, **32**, 185, 1910.

² *Astronomische Nachrichten*, **124**, 121, 1890.

³ *Untersuchungen über den Lichtwechsel Algols*, Leipzig, 1902.

where μ is the albedo of the companion's surface, ds and ds' are surface elements of the two spheres, ρ the distance of the elements, θ, θ' the angles between the normals of the elements and the line joining them, ϕ the angle between the normal of ds' and the line joining the centers of the spheres.

Let κ be the radius of the companion, a the distance between centers, 2δ the apparent diameter of the primary seen from ds' . If the bodies are not too close together we may put

$$\int \frac{\cos \theta ds}{\rho^2} = \pi \sin^2 \delta.$$

Putting also $ds' = \kappa^2 \sin \phi d\phi d\psi$, we find

$$J_2 = J\mu \kappa^2 \int_0^{2\pi} d\psi \int_0^{\frac{\pi}{2}} \sin^2 \delta \cos \theta' \cos \phi \sin \phi d\phi$$

or

$$J_2 = 2\pi J\mu \kappa^2 \int_0^{\frac{\pi}{2}} \sin^2 \delta \cos \theta' \cos \phi \sin \phi d\phi.$$

Substituting

$$\sin \delta = \frac{I}{\sqrt{a^2 + \kappa^2 - 2a\kappa \cos \phi}}, \quad \cos \theta' = \frac{a \cos \phi - \kappa}{\sqrt{a^2 + \kappa^2 - 2a\kappa \cos \phi}},$$

there follows

$$J_2 = 2\pi J\mu \kappa^2 \int_0^{\frac{\pi}{2}} \frac{\sin \phi \cos \phi (a \cos \phi - \kappa)}{(a^2 + \kappa^2 - 2a\kappa \cos \phi)^{3/2}} d\phi,$$

and carrying out the integration,

$$J_2 = \frac{2}{3}\pi J\mu \cdot \frac{2a^3 + \kappa^3 - (2a^2 - \kappa^2)\sqrt{a^2 + \kappa^2}}{a^2\kappa}.$$

We can now put $\frac{\kappa}{a} = \gamma$, and obtain with sufficient approximation¹

$$J_2 = \frac{2}{3}\pi J\mu (\gamma^2 + \frac{3}{4}\gamma^3 + \dots). \quad (3)$$

¹ Equation (3) is the same as Wilsing's corrected by Pannekoek, except for the coefficient of γ^3 which he gives as $\frac{1}{2}$.

In my previous paper, the increase of surface intensity on the brighter side of the companion was called λ_1 , the total increase of radiation being $\kappa^2\lambda_1$, and from (1) and (3)

$$\kappa^2\lambda_1 = \frac{J_2}{J_1} = \frac{2}{3}\mu(\gamma^2 + \frac{3}{4}\gamma^3)$$

or

$$\mu = \frac{3}{2} \cdot \frac{\kappa^2\lambda_1}{\gamma^2 + \frac{3}{4}\gamma^3}. \quad (4)$$

The numerical values of the elements are

$$\kappa = 1.14 \pm 0.05$$

$$a = 4.77 \pm 0.05$$

$$\kappa^2\lambda_1 = 0.049 \pm 0.007$$

which substituted in (4) give $\mu = 1.09$. As pointed out by Wilsing, the integration is extended over too great an area of each sphere, but even limiting ϕ to $\frac{\pi}{3}$ I find $\mu < 1.15$, and we may therefore adopt

$$\mu = 1.10 \pm 0.20$$

where the probable error depends upon the probable errors of κ , a , and λ_1 , almost wholly the last. From the size of the probable error it is evident that μ may be less than unity, but in any event the reflection theory is untenable, which agrees with the conclusion in my paper.

The interpretation to be given to this high value of μ is that the companion of *Algol* receives and emits nearly equal amounts of the radiation to which selenium is sensitive. It is probable that the spectral energy-curves of the two bodies are entirely different, but the integrated effect is practically the same as though the companion reflected all of the light which it receives. At present we know nothing of the spectral type of the companion, but we do know that it is a body which of itself is probably more intense than the sun. Dr. W. J. Humphreys has suggested to me that we should expect the companion to have a low albedo, because of its extremely small density, and that its coefficient of absorption may be something like that of a black body. If this is true, then the absorbed radiation is no doubt re-emitted in quite different form. It is

evident that the observational data are not sufficient to lead us to any final conclusion as to the radiation of the companion, except to state definitely that only a small portion of the extra light from one side can be due to reflection.

It should be noted that *Algol* is not the only case where the companion is known to be brighter on one side, for Dr. R. S. Dugan of Princeton has found the same phenomenon in two other stars, *RT Persei* and *Z Draconis*.¹ Preliminary announcements of the character of the variation of these stars were made by Dr. Dugan in 1908 and 1909, and it is my understanding that the work will soon be published in full.²

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April 6, 1911

¹ *Publications of the Astronomical and Astrophysical Society of America*, **1**, 311 and 320, 1910.

² See *Contributions from the Princeton University Observatory*, No. 1: "The Algol-System *RT PERSEI*," by Raymond Smith Dugan.—Ed.

ON REGULARITIES IN THE SPECTRUM OF NEON

By HERBERT EDMESTON WATSON

In 1908 the author published a paper on the "Spectrum of the Lighter Constituents of the Air,"¹ in which were given the wave-lengths of a number of lines ascribed to neon. As the primary object of the research was to detect, if possible, the presence of a new gas, long exposures were given to the plates, and the accuracy of the measurements was consequently somewhat impaired. It was considered, however, that the values given for the wave-lengths were usually correct to 0.03 Å.U., and this was borne out by the agreement with the previous measurements by Baly.²

The existence of some 200 new lines was determined by these experiments, making the total 321, and it seemed worth while to examine the spectrum with a view to discovering a possible regularity. For this purpose, the wave-lengths were first converted into the corresponding oscillation-frequencies *in vacuo*.

Since the helium spectrum had been found to be capable of resolution into six series of lines with gradually diminishing intensities,³ it was thought at first that such series might also exist in neon, and as two of the helium series consisted of doublets, it was hoped that the detection of similar doublets in neon might indicate lines which belonged to the same series. In the case of helium the constant difference of oscillation-frequency between members of a pair is 1.00, and consequently, if this difference is proportional to the square of the atomic weight, the corresponding value for neon might be about 25. Now there is, as it happens, an unusually large number of oscillation-frequency differences between 25 and 26, but the total number is only 13, and there appears to be no connection between the intensities of the pairs of lines. Consequently, this hypothesis was, for the time being, abandoned.

¹ *Proc. Roy. Soc., A*, **81**, 181, 1908.

² *Phil. Trans., A*, **202**, 183, 1903.

³ Runge and Paschen, *Astrophysical Journal*, **4**, 91, 1896.

The next step was to plot the positions and relative intensities of all the lines on a large scale, and an examination of the map of the spectrum thus produced showed that the lines appeared to be divided into three groups with considerable gaps between them. The first of these groups extends from the extreme red to $\lambda 4071$, and consists of a great mass of lines, 252 in all, among which are many weak ones, especially at the blue end. The second group extends from $\lambda 3754$ to $\lambda 3370$, and contains 29 lines only, but all of these, with the exception of 5 very weak and doubtful ones, are of considerable strength. The third group reaches from $\lambda 3167$ to $\lambda 2736$, there being 40 lines in all, though a subdivision is possible owing to the fact that there is an obvious gap between $\lambda 2911$ and $\lambda 2872$. Also the lines on the less refrangible side of this gap are considerably stronger than those on the other, and among the former no very weak ones are to be found.

This arrangement suggested that the groups might be in some way repetitions of each other, that is to say, there might be constant frequency-differences between certain corresponding lines in them, and consequently these differences were calculated between each line of the second group and all those of the third. The results were indefinite.

After this, the difference between each pair of lines in the second group was determined, and so also for the third group, and it was then found that a distinct regularity existed, inasmuch as many of the lines could be grouped into triplets with constant frequency-differences, the difference between the first and second lines being approximately 1429, and that between the first and third 1847. A search was then made in the rest of the spectrum for more of these triplets, and several were found in the extreme red, but no others seemed to exist. There were, it is true, several other pairs of lines with one of the above differences between them but this is to be expected from considerations of probability, and in no case was the triplet complete.

In addition, on examining the second group, it was found that there were three pairs of lines with a frequency-difference of 1070, the first line in each case being the first member of a triplet. In view of the small number of lines in this group, this could hardly

be accidental, especially as three similar pairs occurred in the third group, and three in the first, and the difference in question did not appear again. It seems, therefore, that in the whole spectrum there are nine quadruplets, and a number of triplets with the same frequency-differences, but with the second line absent. Moreover, it was found that these triplets and quadruplets were not merely groups of three or four lines occurring among a number of others, but that practically all the lines in certain regions of the spectrum were capable of arrangement into such groups. Thus, in the second large division of the spectrum, which practically consists of 24 bright lines, there are three quadruplets and four triplets, in one of each of which a line is missing, and only two lines do not fit into the scheme. The first of these is the strongest line in the whole group, and the second one is brighter than nearly all the others. In the third group, or rather in the first subdivision of it previously mentioned, there are also only two lines which are not members of triplets or quadruplets, while all the rest, 25 in number, fall into these natural groups. It is interesting to note, however, that one line λ 2992 occurs twice. Also, the members of the last two quadruplets are so close together that they appear to have been resolved only in two cases. When the wave-lengths were first published, the line λ 2949 was marked "broad," and is doubtless double, a fact which is also indicated by the abnormal frequency-difference, and it is quite possible that the line λ 2913 is double as well.

On turning to the first group of lines, it is found that not all of them belong to triplets or quadruplets, although most of the stronger ones do. It must be remembered, however, that the numbers representing the intensity according to the usual convention merely indicate which lines are brighter than others, and which are of approximately equal intensity. Actually, the energy corresponding to a line of intensity 10 is probably many thousand times that of one of intensity 1, and this difference is very apparent on visual observation, especially in the case of the present spectrum, for on looking at the region in which the regularities occur with an ordinary spectroscope, 23 very bright lines are seen and no others, unless special precautions are taken. Of these lines, all are mem-

bers of triplets or quadruplets except two, λ 6402 and λ 6074. In addition, the former is the brightest line between the wave-lengths under consideration. It is also interesting to note that if the pressure of the gas is fairly high, say above 5 mm, these 23 lines and two others, λ 7245 and λ 5852, constitute practically the whole of the visible spectrum; and it is remarkable that the latter line, which is the brightest in the entire spectrum, is just outside the region of triplets and quadruplets, and does not take part in their composition. It may also be mentioned that while examining these bright lines with a Hilger constant-deviation spectroscope, an additional very weak one was observed in the extreme red, the wave-length as given by the instrument being about λ 7445.

The following tables show how the lines have been arranged.

QUADRUPLTS

$\frac{10^8}{\lambda}$	A	Int.	Diff.	A	Int.	Diff.	A	Int.	Diff.	A	Int.
14232.22	7024.38	2	1070.33	6533.08	6	1429.78	6383.14	9	1847.20	6217.44	6
14883.08	6717.22	7	69.97	6266.69	6	9.34	6128.63	5	6.62	5975.76	5
15149.28	6599.18	9	70.24	6163.73	6	9.41	6030.20	5	6.95	5882.06	5
26628.6	3754.32	3	69.7	3609.33	3				6.4	3510.87	4
27767.6	3600.32	6	70.2	3466.70	5	9.1	3424.08	3	7.3	3375.74	2
27818.8	3593.69	8	69.7	3460.61	5	9.6	3418.03	5	6.3	3370.02	5
31560.6	3167.62	2	69.0	3063.83	2	8.5	3030.44	2	6.0	2992.57	3
32465.7	3079.31	1	70.0	2981.06	1	30.8					
32468.7	3079.02	1	69.8	2980.81	1	27.8	2949.32	1	7.1	2913.28	2

TRIPLETS

$\frac{10^8}{\lambda}$	A	Int.	Diff.	A	Int.	Diff.	A	Int.
13934.95	7174.25	2	1429.67	6506.69	9	1846.96	6334.65	9
14426.56	6929.78	6	9.64	6304.97	6	6.89	6143.31	7
14969.37	6678.50	9	9.40	6096.36	6	6.85	5945.02	6
27009.9	3701.31	5	9.1	3515.32	5	6.6	3464.46	4
27123.2	3685.86	4	9.3	3501.34	5	7.4	3450.88	4
27148.9	3682.37	4	9.4	3498.19	5	6.8	3447.83	5
27511.8	3633.80	5	9.5	3454.31	5			
31701.7	3153.51	2	9.3	3017.47	3	6.6	2979.94	2
31750.2	3148.70	2	9.0	3013.09	3	6.4	2975.65	1
31759.0	3147.82	1	9.4	3012.25	3	6.2	2974.89	3
31977.4	3126.33	2	9.2	2992.57	3			
32480.2	3077.08	2	8.9	2947.44	3	7.0	2911.55	1
32697.2	3057.51	3	9.0	2929.47	1			

In column 1 is given the oscillation-frequency *in vacuo* of the first line, followed by its wave-length in air and its intensity. The fourth column shows the difference between the *oscillation-frequencies* of the first and second lines, the wave-length and intensity of which follow. The next column gives the difference between the oscillation-frequencies of the first and third lines, and so on. The actual oscillation-frequencies are not given except for the first line, but of course may be calculated from the differences.

With regard to the agreement between the different values for the constant frequency-differences, it may be noted that if the error in the wave-length of a single line is 0.03, that of the difference of two may be 0.06, and the maximum variation is 0.12. This, in the scale of oscillation-frequencies, corresponds roughly to 0.3 for the first group of lines, and 1.0 for the other two, and it will be observed that this limit is rarely exceeded, though it may be remarked that the actual values of the differences in the first group seem slightly larger than the others, and also that those between the triplets are more constant than those between the quadruplets; possibly the lines composing the former are slightly sharper than the others, although no actual difference is apparent. The author's values for the wave-lengths and intensities have been used throughout, as Baly's figures, though possibly rather more accurate, are not complete.

There appears to be no very definite relation between the intensities. Generally speaking, the lines in the first group are brighter than those in the second, and these in turn brighter than those in the third. Also, corresponding lines in the same group have often the same intensities, this being especially well marked in the case of the triplets. The figures representing the intensities in the extreme red are probably far too small, as they show only the extent to which a photographic plate is affected, and in this portion of the spectrum the total energy is, no doubt, considerably greater than that indicated in this way.

It is not proposed to discuss fully a number of interesting points which are raised by the existence of these regularities. The main facts so far ascertained may, however, be outlined. First, if the bright lines only are considered, the spectrum falls naturally

into three groups of lines which diminish in general intensity on approaching the ultra-violet end. The first group consists of one very bright line, one weaker line, three quadruplets, and three triplets; the second of one very bright line, one weaker line, three quadruplets, and four triplets; while the third group contains also two bright lines, three quadruplets, and six, or possibly only five, triplets.

This arrangement naturally suggests a principal series and two subordinate ones, the second, or both of the latter, consisting of triplets or quadruplets, or possibly a principal and two subordinate series of quadruplets alone, and others of triplets alone, especially as a grouping in threes seems to predominate; but even if some such connection does exist, it would be exceedingly difficult to determine, since there are at present only three members of each series.

The whole arrangement also strikingly resembles the blue portion of the red argon spectrum investigated by Rydberg.¹ This author found that all the lines between certain limits, except a few very weak and doubtful ones, could be arranged in a scheme of 7 quadruplets, 6 triplets, and 10 doublets, in a very similar manner to the neon lines above, but the mean frequency-differences from the first line were in this case 846.5, 1649.7, and 2256.7. Two lines, however, were not included, and one of these was the brightest of all those under consideration. It seems hardly possible that such a coincidence can be accidental.

With regard to the other and weaker lines of the spectrum, which consist of a number in the first group, and all those in the second subdivision of the third group, a regularity is not at present apparent. A partial search has so far failed to reveal any constant frequency-differences, but it by no means excludes their existence. As, however, there are in all some 25,000 possible differences, the work is necessarily slow. Another possibility is that these lines are the components of a number of series similar to those in helium, a supposition which is strengthened by the fact that there are a great many weak lines close together at the blue end of the first group. From the point of view of intensity alone,

¹ *Astrophysical Journal*, 6, 338, 1897.

this portion of the spectrum is somewhat analogous to the secondary spectrum of hydrogen, and while there can be no doubt that there is some relation between the lines composing it, the solution of the problem is not easy. The investigation both of these lines and of the brighter ones is being continued, and it is hoped that by means of methods which are not solely mathematical, some further light may be thrown on the true constitution of this remarkable spectrum.

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APPLICATION OF THE INTERFERENCE METHOD TO THE STUDY OF NEBULAE

BY CH. FABRY AND H. BUISSON

The spectroscopic study of the sidereal universe has been made almost solely with a single form of apparatus, the prism spectroscope, the general form of which has remained unchanged. It is only in very exceptional cases that gratings have been employed. It is doubtless necessary to conclude that the prism spectroscope is the apparatus best adapted to that class of researches and although in the future it will probably continue to play a leading part, it is possible now to consider other methods which may be able to contribute, at least in certain cases, to the progress of our knowledge of stellar astronomy.

Interference methods in varied forms have shown their efficiency in the analysis of light both in laboratory researches and in the study of the sun. Our present work has for its single purpose to show that it is neither impossible nor difficult to apply these methods to certain problems of sidereal astronomy.

Interference methods may be employed with special convenience when the source of light under investigation emits a small number of monochromatic radiations; the case of continuous spectra having dark lines is less simple. We have applied our method to the study of nebulae whose spectra consist of a small number of bright lines.

The interference apparatus consists of a film of air between two plane-parallel surfaces covered with a thin coat of silver. The fringes produced are rings situated at infinity. The observing apparatus, visual or photographic, should give a sharp image of those rings. It is desirable that there should be no mixing of the radiations emitted by the different parts of the object, and consequently that the sharp image of the nebula should be formed in the same plane as that of the rings. The most simple manner of arriving at this result would be to place the interferential apparatus in front of the entire observing apparatus; but then we should be limited as to the diameter of the objective by the size of the

silvered film; and further, the apparent diameter of the rings would be very large with respect to that of the nebula.

The following arrangement overcomes both these difficulties. The interference apparatus is placed at the end of the telescope, set upon the nebula for an eye focused for infinity and consequently forming an afocal system; on looking through this, if the eye is focused for infinity, it will see a sharp image of the nebula on which the interference rings will be projected. It is not possible to use more than a small surface of silver, hardly larger than that of the ocular ring; the apparent diameter of the rings is not changed, while that of the nebula is multiplied by the enlargement of the telescope. For photographic observations the light which has traversed the above system is collected by an objective of short focus in the focal plane of which are superposed the real image of the nebula and that of the ring. Finally, it is possible to examine the image visually with an eyepiece.

We have made a practical application of this plan to the equatorial of the Observatory of the University of Marseilles. The objective has a diameter of 26 cm, and a focal length of 3.10 m. Having removed the eye-end of the telescope, we replaced it by the apparatus represented in Fig. 1. *A* is an eyepiece with two lenses forming an optical system of 4 cm focal length, the first focus of which is in the focal plane *F* of the telescope objective. On leaving this eyepiece, the rays of the nebula give an image at infinity, enlarged eighty times. The light then traverses the interference apparatus *B*, which gives its system of interference rings. A microscope objective *C*, of 4 cm focal length, forms in its focal plane *P* a real image of the nebula, of the same size as that which would be directly given by the telescope objective; this image is crossed by the interference fringes. For photographic observations, the plate is placed at *P*. In visual observations we see the superposed image of the rings and of the nebula through a second eyepiece *D* having a focal length of 2.5 cm; the nebula is then seen with an enlargement of 120, and the rings

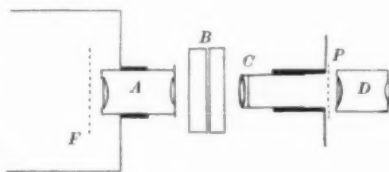


FIG. 1

with an enlargement of 1.6. The free aperture of all the lenses is such that there is no loss of light.

The interference apparatus is of the type having a fixed difference of path, which is called the *étalon interférentiel*.¹ It is difficult to apply this form of construction when the film of air has a thickness less than 1 or 2 mm; for thicknesses less than this the two silvered surfaces are simply separated by three bits of steel of suitable diameter cut from the same rod. Springs with an adjustable pressure hold the silver surfaces against the pieces of steel and permit us to obtain parallelism.

The quality of the silver surfaces is of great importance. If they are too thick, the proportion of the light transmitted is very small; if they are too thin, the reflecting power is very little, and the interferences are not sharp. We have employed films silvered by impact at the cathode. Each of the surfaces transmits for the green mercury line about 20 per cent of the incident light and reflects 50 per cent. The interference apparatus may be inclined at a slight angle to the beam of light, which permits us to displace the system of rings with respect to the image of the nebula.

The total weight of everything attached to the tube of the telescope is only 3 kilograms.

We have examined only the nebula in *Orion*. Observing visually, we established without difficulty the existence of interference rings, in successively employing differences of path of 0.6, 2, and 5 mm. The rings thus observed are due to the ray at λ 5007, which is the most intense of the visible lines in the spectrum of that nebula.

We have also made an attempt at a photographic observation. In order not to increase the time of exposure in this first experiment we worked with all the rays without interposing any absorbing medium. Since the objective of the equatorial was achromatized for the visual rays, it was impossible to obtain a good image of the stars and of the nebula: the images of stars are circles of considerable diameter, although we had made the setting for the mean of the photographic rays. That had no effect on the sharpness of the rings, the images of which are given solely by the objective *C*. With a difference of path of 0.6 mm and an

¹ Ch. Fabry and A. Perot, *Astrophysical Journal*, **15**, 81, 1902.

exposure of $1\frac{1}{4}$ hours, we obtained perfectly sharp rings on a Lumière Sigma plate. Furthermore, the images of the stars destroy part of the field. The strongest rays in the photographic spectrum of the nebula of *Orion* are the hydrogen line, γ , at λ 4341, and the line of unknown origin at λ 3727; the rings photographed result from the superposition of the rings due to these two rays.

These first attempts have no other object than to show the possibility of applying our method. We hope to be able to employ it with instruments which are more powerful and better adapted to the purpose, in particular with a reflecting telescope. All the difficulty from lack of achromatism would thus be avoided. Furthermore, the use of an objective of large diameter allows us to employ a great amount of light. It would then be possible to combine the different lenses of the apparatus in such a way that the ratio of aperture to focal length of the instrument should be large, which would permit short exposures of the photographs without making the images too small. This result may indeed be obtained whatever is the ratio of the aperture of the telescope objective. Under the conditions of our experiments, the ratio of aperture of a complete system would be only 1:12; with a large objective, it would probably not be impossible to go to 1:4.

The use of the interference method will be able to yield certain interesting results. It would be easy to measure the wave-lengths of the different rays with great precision and thus to derive the radial velocity of the object, in using the hydrogen lines. The variations of wave-length from one point to another would give us the circulatory movement of the gas. The determination of the limits of interference would give the size of the different lines; and an indication as to the temperature would be furnished by the size of the hydrogen lines, while the size of the lines of unknown origin would give us a clue to the atomic weight of the gas which forms them.

We have been able to make this experiment by the courtesy of M. H. Bourget, director of the Observatory of the University of Marseilles, who has been good enough to permit us to employ the equatorial of the observatory and has given us his personal assistance in its use. We extend to him our very sincere thanks.

UNIVERSITÉ DE MARSEILLE
March 1911

OBSERVATIONS OF *NOVA LACERTAE* AT THE YERKES OBSERVATORY

By EDWIN B. FROST

The temporary star in *Lacerta* announced by Espin on December 30, 1910, has been observed here in part as follows.

The position of the *Nova* was accurately determined with the micrometer of the 40-inch telescope by Mr. Barnard as R.A. $22^h 32^m 11^s.79$, Dec. $+52^\circ 15' 19''.8$ (1911.0). He is also making a triangulation of the neighboring stars, which will be published elsewhere. Upon examining photographs of this region which he had taken in previous years, Mr. Barnard found¹ a star of about the fourteenth magnitude in exactly the position of the *Nova* on four dates, namely:

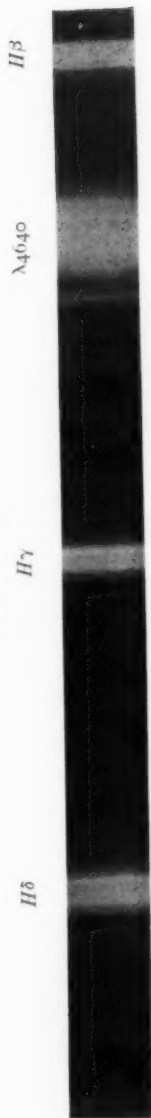
1907, August 7,	Exposure ²	$0^h 47^m$	Bruce	Telescope,	10-inch
				and 6-inch lenses	
1909, August 22,		5 55	Bruce	Telescope,	10-inch
				and 6-inch lenses	
1909, August 24,		3 55	Bruce	Telescope,	10-inch
				and 6-inch lenses	
and					
1893, October 11,		6 21	Willard	Lens, Lick Observa-	
				tory	

He has also taken several new photographs of the field of the *Nova* with the 10-inch and 6-inch lenses. In Plate XII, Fig. 1, is reproduced the photograph of August 7, 1907, with the 10-inch lens, enlarged twelve times. The arrow points at the *Nova*. Fig. 2 shows the same field taken with the two-foot reflector by Mr. Slocum on January 30, 1911, with an exposure of 25 minutes. It is enlarged sixfold. The lettering of the stars is that which will be used in Mr. Barnard's triangulation. The *Nova* is designated by *N*.

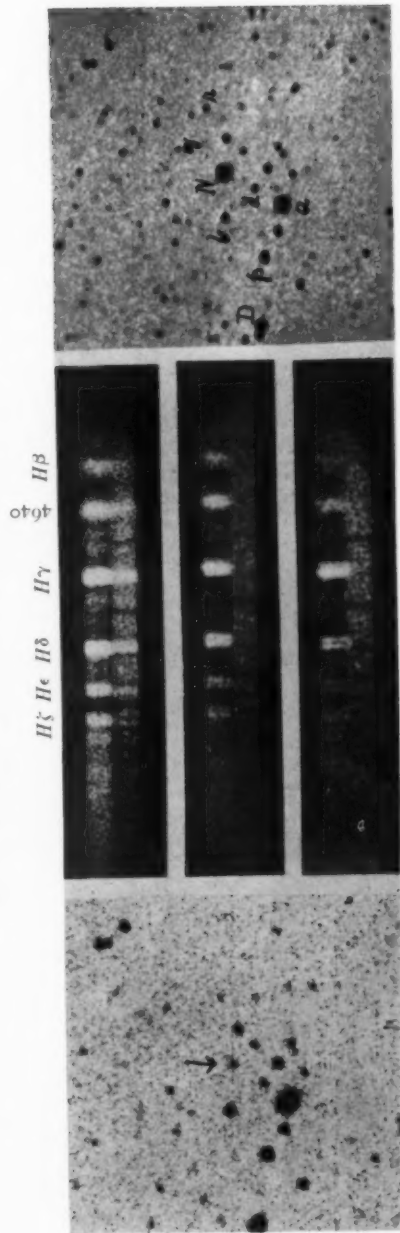
¹ *Astronomische Nachrichten*, 187, 63, 1911.

² Mr. Barnard advises me that the two plates in 1909 were exposed by Mr. Morehouse.

PLATE XII



3. Spectrum taken with Bruce spectrograph, January 3, 1911 (Frost)



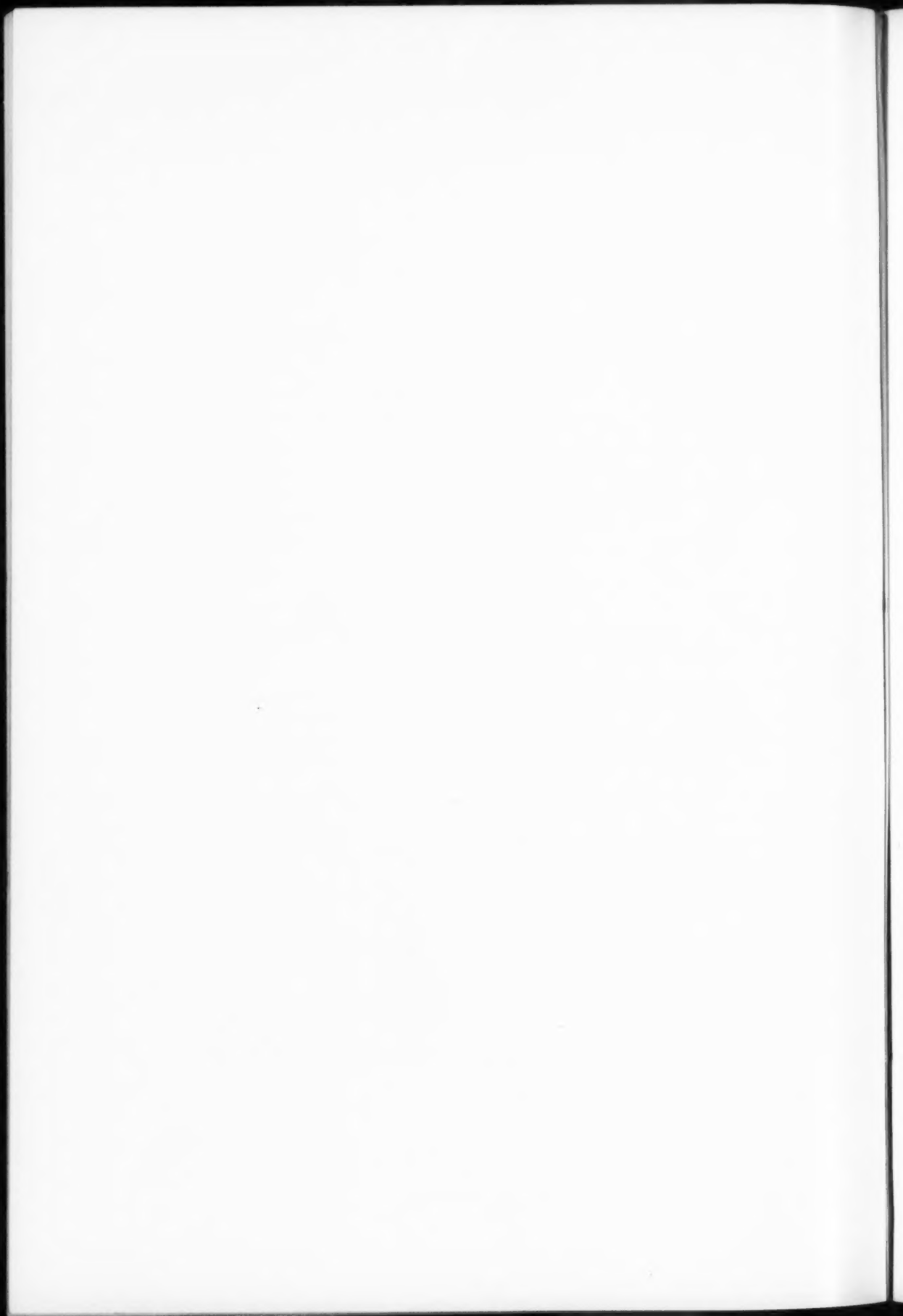
1. August 7, 1907 (Barnard)
10-inch Bruce doublet

Three spectra of *Nova* (above) and nearby star
(below) taken with prismatic camera (Parkhurst)

4. January 23, 1911
5. January 30
6. February 22

2. January 30, 1911 (Slocum)
Two-foot reflector

NOVA LACERTAE



The first photographs of the *Nova* with the reflector, by Messrs. Parkhurst and Slocum, suggested the possibility of some nebulosity around the star; but the telescope had been put out of adjustment on account of some recent alterations, and subsequent exposures by Mr. Slocum, after readjustment of the instrument, did not confirm the presence of any nebulous surroundings of the star.

Photographs of the *Nova* have been obtained on two nights by Mr. Slocum with the 40-inch telescope, for the subsequent determination of its parallax, if the star remains sufficiently bright.

On the nights of January 28 and February 4, 1911, Mr. Parkhurst made three sets of measures of the brightness of a sequence of stars near the *Nova*, using the equalizing-wedge photometer attached to the 40-inch telescope. Assuming for the present that the magnitude of star $a = +51^{\circ}3420$ is 8.80, as given in the *B.D.*, his values are as follows:

$$\begin{array}{llll} a = 8.80 & . & . & d = 12.20 \\ D = 10.09 & . & . & r = 12.93 \\ p = 11.57 & . & . & q = 14.46 \\ b = 12.07 & & & \end{array}$$

Mr. Parkhurst calls attention to the strongly actinic quality of the light of the *Nova*, in spite of its decidedly red color. The photographs with the two-foot reflector indicate a color-index like that of an A star. As an explanation of the anomaly that a star apparently so red should photograph as quickly as a white star, Mr. Parkhurst suggests that much of the light comes from the unusual extension of the continuous spectrum in the ultra-violet. This is clearly seen on the uppermost of the three objective-prism plates (for January 23) shown in Plate XII, and it would appear to be an entirely adequate explanation.

Mr. Barnard has referred (*loc. cit.*) to the focal peculiarity of the star when observed with the forty-inch telescope. As was the case with *Nova Geminorum* in 1903, a sharp crimson image is formed 9 mm farther from the objective than the usual image, which latter agrees in position with that for ordinary stars, and is of a whitish color surrounded by a crimson glow. The strong concentration of the light at *Ha* would sufficiently account for this appearance.

Visual observations of the spectrum were made by the writer at the forty-inch telescope on December 31 and subsequently, with a small ocular spectroscope. Measurements were not possible, but the appearance was that typical of a nova, recalling early views of *Nova Aurigae* in 1892. *H α* was brilliant, and strong bright lines could be seen in the yellow and green, but could not be identified with certainty. The dark components could not be distinguished in that region of the spectrum, but could be seen faintly in the violet.

With the exception of the spectrogram secured with the Bruce spectrograph on January 3, the photographs of the spectrum have been obtained by Mr. Parkhurst with our efficient Zeiss doublet of "ultra-violet" glass (of aperture 14.5 cm and focal length 81.4 cm) with 15° objective-prism of U.V. flint. The scale is very small, 3.0 mm from *H β* to *H θ* , but much useful information may be gained from the plates of stars quite beyond the reach of our other spectrographs. The list of negatives thus far obtained is as follows:

No.	Date	Exposure	No.	Date	Exposure
414.....	1910 Dec. 31	12 ^m	420.....	1911 Jan. 22	.. ^m
415.....	31	60	421.....	23	60±
416.....	31	40	422.....	29	30
417.....	1911 Jan. 16	..	423.....	30	22±
418.....	17	42	424.....	Feb. 22	37
419.....	21	60	427.....	March 19	69
			428.....	April 6	60

The plates of January 23, January 30, and February 22 are reproduced, with 13-fold enlargement, in Plate XII. Of course this is an excessive enlargement for such negatives, on coarse-grained emulsions of high speed, but it is necessary if the engraving is to show any detail. The star *B.D.* 51°3420 (No. 7788 A.G., Cambridge, U.S.) is so close to the nova that it serves in a manner for a comparison spectrum, although shifted some 150 Å.U. toward the violet by the difference in declination of the two stars. Its spectrum falls just below that of the nova on the three plates, but on the upper one it is overlapped by the stronger lines of the nova, due to an excess of broadening in right ascension.

Only three of these objective-prism plates, namely, those taken on December 31, precede in time the Bruce spectrogram, which may now be described. Its horizontal enlargement on Plate XII is about $4\frac{1}{2}$. It will be understood that the fine lines shown are

	Violet Edge	Red Edge	Mean or Center	Displacement from Normal Position
Bright $H\epsilon$	3960.6	3984.6	(3972.6)	+2.4 Å.U
1st dark $H\delta$	4084.2	4086.5	(4085.4)	-16.5
"Split"			4086.9	-15.0
2d dark $H\delta$	4087.3	4090.5	(4088.9)	-13.0
Bright $H\delta$	4090.5	4116.7	(4103.6)	+1.7
Dark in bright δ			4110.3	+8.4
Adjacent bright max. real?			4112.2	+10.3
1st dark $H\gamma$	4322.0			-18.6
Possible "split"			4325.8	-14.8
2d dark $H\gamma$		4329.6		-11.0
Bright $H\gamma$	4329.6	4356.2	(4342.9)	+2.3
Dark in bright γ			4349.5	+8.9
Narrow adjacent bright			4351.3	+10.7
Faint bright region.	4507.5 ±	4525.7 ±		
Bright region.	4581.7 ±	4589.9 ±		
Max. within this.			4583.7	
Broad 4640 band.	4600	4708	(4654)	
Possible dark therein.			4613.5	
Apparent bright max. in band.			4640.0	
Apparent dark.	4838.4			-23.1
Apparent "split"			4842.6	-18.9
2d dark		4847.3		-14.2
Bright $H\beta$	4847.3	4879.3	(4863.3)	+1.8
1st bright max.			4860.8	-0.7
2d bright max. dupl.?			4875.2	+13.7
Dark in bright β			4890.4	
Bright patch (helium)			4922	
Faint bright marking (helium)			5016	

unavoidably introduced in the process of vertical enlargement. The essential features are the broad bright lines of hydrogen and that at λ 4640; the bright maxima and possibly dark shadings within these bright lines, and the dark lines adjacent to their violet edges, which are best seen in case of $H\gamma$ and $H\delta$. The negative was obtained with an exposure of 2 hours on January 3, mid-exposure

at 12^h 46^m G.M.T., with mean hour angle 3^h 9^m West. The slit-width was 0.10 mm, and the comparison spectra were *Ti* and *Fe*. At *Hγ* the scale of the negative is 1 mm = 26.0 Å.U.

I made settings upon the edges and maxima of all the lines, as accurately as their very diffuse nature would permit, from which the following necessarily rough wave-lengths were deduced. The word "split" denotes a narrow separation between two components of a line, without affirming whether it is a reversal, a narrow portion of continuous spectrum, or an actual narrow line.

The value in the fourth column, entitled Mean or Center, is inclosed in parentheses when it represents the mean of the wave-length for the two edges of the band; otherwise the wave-length is that of the center of the line, upon which the setting was made.

The constitution of the hydrogen lines will be better indicated if the data of the fifth column are summarized, thus giving the displacements in Å.U. of the particular feature from its normal position.

Hydrogen Line	First Dark	Second Dark	"Split"	Center of Broad Bright	Dark within Bright	Narrow Bright
ϵ .....	.....	.....	.....	+2.4	.....	.....
δ	-16.5	-13.0	-15.0	+1.7	+8.4	+10.3
γ	-18.6	-11.0	-14.8	+2.3	+8.9	+10.7
β	-23.1	-14.2	-18.9	+1.8	.....	+13.7
Mean	-19.4 Å.U.	-12.7 Å.U.	-16.2 Å.U.	+2.0 Å.U.	+8.7 Å.U.	+11.6 Å.U.

Too much weight should not be attached to results depending upon a single spectrogram, and the settings on the edges of such diffuse lines may be grossly in error; but the tolerable accordance of the displacements for the different lines gives some confidence as to the order of their magnitude. If the Doppler effect were thought to be involved (which seems highly improbable), the velocities corresponding to the displacements would for the mean of the various columns be about -1300, -880, -1100, +120, +580, and +760 km per second.

These displacements and velocities are quite parallel to those observed in case of *Nova Aurigae*, as well as *Nova Persei*. The

doubt still expressed in some quarters as to whether *Nova Lacertae* is a variable or a temporary should be wholly dispelled by the similarity of the spectrum to that of other novae.

It should be noted that such displacements may be to a considerable extent spurious, both for the dark and the bright components. This is particularly true for the dark components, which may be much narrowed on the less refrangible side by the overlapping bright radiations. However, if the "split" seen between the first and second dark components (which, by the way, was also noted in *Nova Aurigae*) is a genuine reversal, it may represent the center of the broad dark line.

The spectrogram under discussion unfortunately does not include the neighborhood of K with sufficient strength to testify whether or not K is sharp and narrow, as it was in *Nova Persei*. The plates obtained with the prismatic camera do not show it, but a very fine line could hardly be detected owing to the exceedingly small scale and great breadth of the neighboring lines.

It is much regretted that no other evening was available for the Bruce spectrograph on which the weather conditions were such as to make it worth while to attempt an exposure, until the star's brightness had declined too far.

OBJECTIVE-PRISM PLATES

I have measured the five best plates obtained with the prismatic camera, deriving the relative wave-lengths from a curve drawn from measures on other stars on the plates. The wave-length of the center of bright $H\gamma$ was assumed to be normal. The subsequent alterations in bright $H\gamma$, however, are too great for it to be a safe standard of reference. It must therefore be understood that the measures are only relative. The uncertainty of settings on the edges of such bright lines is very great, and a unit of ten Ångströms would be more suitable.

The widths of the lines are of the same order as for the spectrogram of January 3: on the later plates the duplicity of the bright lines of hydrogen is more obvious. The plate of February 22 shows bright $H\gamma$ very distinctly triple, the central component the strongest in intensity. $H\delta$, however, is clearly double, not

triple; but on April 6 $H\gamma$ has only two, approximately equal components.

WAVE-LENGTHS DERIVED FROM CURVE, THE SETTING FOR BRIGHT $H\gamma$ BEING ASSUMED

	No. 418 Jan. 17	No. 421 Jan. 23	No. 423 Jan. 30	No. 424 Feb. 22	No. 428 April 6
$H\eta \lambda 3835$ .....	....	{ 3819 3845	....	....	....
V.E. of dark, adjacent to	....	3850	....	....	....
$H\zeta$ bright	3880 3898	{ 3872 3901	3881 3895	3887	3850 3875
$H\epsilon$ bright	3963 3980	{ 3958 3990	3963 3982	3960 3984	3955 3978
V.E. of dark, adjacent to	....	4069	....	....	4060
$H\delta$ bright	4090 4106	{ 4082 4111	{ 4085 4115	4090 4110	4082 4102
V.E. of dark, adjacent to	....	4288	4298	....	4283
$H\gamma$ bright	4332 4348	{ 4317 4364	4320 4298	4328 4348 4375	4340 4364
Very faint bright	4479	4464	....	....	....
V.E. dark, adjacent to	....	4550	....	....	....
$\lambda 4640$ bright	4648	{ 4610 4672	{ 4619 4670	{ 4616 4675	4628
$H\beta$ bright	4882	{ 4835 4900	4860	4865	4863
Faint bright .....	....	4987	....	....	....
Faint bright .....	....	5045	....	5016	5013

Measures on edges are connected by braces; otherwise the settings were on centers of bands or of their separate components. V.E. denotes edge toward violet.

On the earlier spectrograms the intensities of the bright lines $H\gamma$ and $H\delta$ do not differ more than would result from the fact that the camera is focused for them; but subsequently $H\gamma$ plays a predominant part in the emission of light, and the relative waning of the helium lines $\lambda 4922$ and 5016 and of $H\beta$ is marked.

It is not possible to say from the evidence of plate 428 (April 6) whether the transformation to the nebular spectrum has begun; the scale of the plates is too small to allow us to decide whether the line previously at $\lambda 5016$ (helium) has been replaced by $\lambda 5007$,

the chief nebular line. The change in appearance of $H\delta$ since February 22 is not appreciable; at $H\gamma$ the change is the return from a triplet to the double line previously present.

The position of the star is such that these small-scale spectrograms will presumably continue to be secured until the star becomes too faint to be followed further.

YERKES OBSERVATORY

May 2, 1911

ADDED TO PROOF SHEETS

MAY 15, 1911

Spectrograms obtained by Mr. Parkhurst on May 4 and 6 show a marked increase in intensity of the band near $\lambda 5000$. Settings on the center of this band, reduced on the assumption that the structure of $H\gamma$ is the same as on April 6, yield a wavelength of 5000, with edges roughly at $\lambda 4962$ and $\lambda 5048$. This may therefore be regarded as the first nebular line, $\lambda 5007$, although the second nebular line, $\lambda 4959$, cannot be seen separately, so that we cannot assert that it is present. The band is not sufficiently resolved so that we can declare whether the two helium lines, $\lambda 4923$ and $\lambda 5016$, have retired from the spectrum or are included within the broad band. The complex character of all the hydrogen lines is maintained as on April 6, and their appearance is not obviously different from that on the plates taken in January and February, excepting the period when $H\gamma$ was triple.

PHOTOGRAPHIC DETERMINATIONS OF STELLAR
PARALLAX MADE WITH THE YERKES
REFRACTOR. VI

BY FRANK SCHLESINGER

Lalande 39866 ($20^h 35^m, +4^\circ 37'$)

This 8th-magnitude star has a proper motion of a little less than $1''$ a year. The fourteen plates secured were measured by Miss Ware.

TABLE I
PLATES OF *Lalande 39866*

No.	Date	Hour Angle	Observers	Quality of Images	Remarks
377....	1904 July 10	-0.5	S, Su, S	Fair	Star (15) not measurable on second exposure
431....	Aug. 25	+0.8	S, Su, S	Fair	
441....	Aug. 27	-0.6	S, Su, S	Fair	
447....	Sept. 4	+0.2	S, Su, S	Fair	
457....	Sept. 11	-0.3	S, Su, S	Fair	
509....	Oct. 30	+0.2	S, S, S	Good	
698....	1905 June 24	+1.2	Su, F	Poor	
704....	July 15	+0.1	F, Su, F	Good	
752....	Sept. 2	+0.8	Su, Su	Poor	
758....	Sept. 10	+1.5	Su, Su, Su	Good	
768....	Sept. 12	+0.8	Su, Su, Su	Poor	
939....	1906 June 5	-0.4	Su, J, Su	Good	
940....	June 8	-1.4	Su, Su	Poor	
941....	June 8	-1.1	Su, J, Su	Poor	

COMPARISON STARS

No.	DIAMETER	X (longitude)	Y (latitude)	DEPENDENCE	
				Computed	Adopted
4.....	0.72	-362	-168	+ .234	+ .20
15.....	0.64	-167	+112	+ .093	+ .10
30.....	0.63	+167	- 98	+ .208	+ .30
31.....	0.73	+118	+217	+ .084	+ .10
35.....	0.84	+244	- 63	+ .291	+ .30
Parallax star.	1.41	+ 31	- 58		

TABLE 2
REDUCTIONS FOR *Lalande 39866*

Plate	Solution (<i>m</i>)	Weight (<i>p</i>)	Parallax Factor (<i>P</i>)	Time in Days (<i>t</i>)	Residual (<i>v</i>)	$\sqrt{p \cdot v}$ in Arc
377.....	0.138	0.8	+0.413	-328	+ .009	+ .02
431.....	0.176	0.7	-0.346	-282	+ .27	+ .06
441.....	0.153	0.7	-0.378	-280	+ .2	.00
447.....	0.092	0.7	-0.499	-272	- .62	- .14
457.....	0.150	0.7	-0.599	-265	- .7	- .02
509.....	0.206	0.9	-0.989	-216	+ .17	+ .04
698.....	0.440	0.3	+0.644	+ 21	+ .18	+ .03
704.....	0.445	0.9	+0.337	+ 42	+ .4	+ .01
752.....	0.465	0.3	-0.467	+ 91	+ .3	.00
758.....	0.467	0.9	-0.583	+ 99	+ .1	.00
768.....	0.483	0.4	-0.610	+ 101	+ .15	+ .03
939.....	0.727	0.9	+0.858	+ 367	- .2	- .01
940.....	0.725	0.3	+0.830	+ 370	- .7	- .01
941.....	0.725	0.5	+0.830	+ 370	- .7	- .01

The normal equations are:

$$\begin{aligned}
 +3.584\pi + 8.888\mu - 0.812c &= +0.521 \\
 +58.740 - 3.989 &= +3.620 \\
 +9.000 &= +3.217
 \end{aligned}$$

These yield

$$\begin{aligned}
 c &= +0.397 \\
 \mu &= +0.0848 = +0''.226 \\
 \pi &= +0.0251 = +0''.067 \pm 0''.022
 \end{aligned}$$

Probable error corresponding to unit weight, $\pm 0.0125 = \pm 0''.033$

The residual for Plate 447 is unusually large, but a solution without this plate yields almost precisely the same parallax ($+0''.066$) with, however, a much smaller probable error ($\pm 0''.010$). Not to over-estimate the accuracy of our result, the parallax from the original solution is regarded as definitive.

The only other determination of this parallax that has been published is by Chase, $+0''.05 \pm 0''.047$.

Groombridge 3689 ($22^h 3^m, +52^\circ 39'$)

This 8th-magnitude star has a proper motion of $0''.6$ per annum. The sixteen plates secured were measured in right ascension and in declination and the parallax was independently determined from the shifts in these two directions. All the measurements were made by Miss Ware.

TABLE I
PLATES OF *Groombridge 3689*

No.	Date	Hour Angle	Observers	Quality of Images	Remarks
50....	1903 July 19	-0 ^h 7	S, Su, S	Good	Telescope East
170A ..	Nov. 26	+0.7	S, S, S	Fair	
181....	Dec. 6	+1.3	S, S, S	Fair	
361....	1904 June 12	-2.0	S, Su, S	Good	Second exposure fair
372....	June 19	-2.0	S, Su, S	Good	
379....	July 10	-0.3	S, Su, S	Good	
381....	July 16	-1.4	S, Su, S	Fair	
390....	July 17	-1.8	S, Su, S	Fair	Images slightly triangular
397....	July 24	-1.7	S, Su, S	Fair	
458....	Sept. 11	-1.2	S, Su, S	Fair	
711....	1905 July 22	-1.3	Su, F	Fair	
716....	July 23	-1.2	F, Su, F	Fair	
721....	July 25	-0.5	F, Su, F	Poor	
794....	Oct. 1	-2.0	Su, Su, Su	Good	
796....	Oct. 3	-1.1	Su, J, Su	Good	
806....	Oct. 7	-0.4	Su, J, Su	Good	

COMPARISON STARS

No.	DIAMETER	X (right ascension)	Y (declination)	DEPENDENCE	
				Computed	Adopted
6.....	0.50	-262	+140	+ .213	+ .21
9.....	0.82	-206	- 94	+ .072	+ .07
15.....	0.52	- 57	+174	+ .269	+ .27
16.....	0.52	- 36	- 87	+ .105	+ .11
21.....	0.45	+164	+ 42	+ .221	+ .22
25.....	0.64	+397	-175	+ .120	+ .12
Parallax star.	1.21	- 5.7	+ 49.1		

TABLE 2
REDUCTIONS IN RIGHT ASCENSION FOR *Groombridge 3689*

Plate	Solution (m)	Weight (p)	Parallax Factor (P)	Time in Days (t)	Residual (v)	$\sqrt{p \cdot v}$ in Arc
50.....	0.493	0.8	+0.509	-385	-.033	-.08
170A.....	0.456	0.7	-0.923	-255	+ 13	+.03
181.....	0.438	0.7	-0.892	-245	+ 1	.00
361.....	0.326	0.9	+0.876	- 56	- 16	-.04
372.....	0.348	0.9	+0.825	- 49	+ 10	+.03
379.....	0.345	0.8	+0.613	- 28	+ 21	+.05
381.....	0.324	0.7	+0.537	- 22	+ 3	+.01
390.....	0.336	0.7	+0.525	- 21	+ 16	+.04
397.....	0.321	0.6	+0.428	- 14	+ 6	+.01
458.....	0.293	0.7	-0.328	+ 35	+ 11	+.02
711.....	0.101	0.5	+0.460	+349	- 8	-.02
716.....	0.125	0.7	+0.446	+350	+ 17	+.04
721.....	0.081	0.4	+0.418	+352	- 26	-.04
794.....	0.085	0.8	-0.598	+420	+ 24	+.06
796.....	0.031	0.9	-0.622	+422	- 29	-.07
806.....	0.045	0.8	-0.668	+426	- 12	-.03

The normal equations are:

$$\begin{aligned}
 +4.848\pi - 3.772\mu + 1.065c &= +0.572 \\
 +85.615\pi + 8.280\mu &= -2.378 \\
 +11.600\pi &= +3.064
 \end{aligned}$$

These yield

$$\begin{aligned}
 c &= +0.304 \\
 \mu &= -0.0569 = -0''.151 \\
 \pi &= +0.0069 = +0''.018 \pm 0''.014
 \end{aligned}$$

Probable error corresponding to unit weight, $\pm 0.0115 = \pm 0''.031$

TABLE 3
REDUCTIONS IN DECLINATION FOR *Groombridge 3689*

Plate	Solution (<i>l</i>)	Weight (<i>p</i>)	Parallax Factor (<i>P</i>)	Time in Days (<i>t</i>)	Residual (<i>v</i>)	$\sqrt{p \cdot v^2}$ in Arc
50.....	0.364	0.8	+0.858	-385	-0.013	-0.03
170A.....	0.304	0.7	-0.224	-255	+5	+0.01
181.....	0.292	0.7	-0.374	-245	+1	.00
361.....	0.245	0.9	+0.501	-56	-6	-0.02
372.....	0.248	0.9	+0.500	-40	-4	-0.01
379.....	0.264	0.8	+0.802	-28	+13	+0.03
381.....	0.254	0.7	+0.843	-22	+4	+0.01
390.....	0.231	0.7	+0.849	-21	-18	-0.04
397.....	0.263	0.6	+0.888	-14	+14	+0.03
458.....	0.251	0.7	+0.800	+35	+22	+0.05
711.....	0.129	0.5	+0.877	+349	+7	+0.01
716.....	0.127	0.7	+0.882	+350	+6	+0.01
721.....	0.105	0.4	+0.891	+352	-17	-0.03
794.....	0.094	0.8	+0.603	+420	+5	+0.01
796.....	0.094	0.9	+0.577	+422	+7	+0.02
806.....	0.060	0.8	+0.526	+426	-25	-0.06

The normal equations are:

$$\begin{aligned}
 +5.752\pi + 8.524\mu + 7.000c &= +1.395 \\
 +85.615\pi + 8.280\mu &= -0.927 \\
 +11.600\pi &= +2.440
 \end{aligned}$$

These yield

$$\begin{aligned}
 c &= +0.217 \\
 \mu &= -0.0348 = -0''.093 \\
 \pi &= +0.0299 = +0''.080 \pm 0''.018
 \end{aligned}$$

Probable error corresponding to unit weight, $\pm 0.0078 = \pm 0''.021$

The mean by weight of the two determinations is

$$+0''.041 \pm 0''.020$$

I have increased the probable error of this mean over its theoretical value in view of the discordance of the two results.

Plates 170A and 181 were taken with the telescope east of the pier and at hour angles that differ considerably from those for

the other plates. A solution in right ascension without them gives the following:

$$c = +0.298$$

$$\mu = -0.0548 = -0''.146$$

$$\pi = +0.0172 = +0''.046 \pm 0''.025$$

Probable error corresponding to unit weight, $\pm 0''.032$

This value differs by only a few thousandths of a second from that obtained by uniting the two determinations from all the plates, and the latter was allowed to stand as the definitive parallax. We see from Table 3 that if we omit Plates 170A and 181, the parallax factors in declination for the other plates differ little from each other, and that it is useless to attempt a least-squares solution in this co-ordinate without these two plates.

With the Yale heliometer Dr. Chase has obtained for this parallax $+0''.03 \pm 0''.047$. Professor Flint kindly informs me, in advance of publication, that his second series with the transit circle at Madison yields $0''.00 \pm 0''.028$.

Krüger 60 ($22^h 24^m, +57^\circ 12'$)

This star is one of a wide double discovered in 1873 during the progress of the work for the *Astronomische Gesellschaft Catalog*. In 1890 Burnham found that the brighter component is itself a double; and Doolittle and Barnard have since shown that the latter is a binary with comparatively rapid orbital motion. The star was put upon my observing list at the suggestion of Professor Barnard, who was at the same time making a series of measurements for the same purpose with the micrometer of the 40-inch, and who surmised from general considerations that the parallax of this system must be large. In the *Astrophysical Journal*, 20, 128, 1904, I published a preliminary value¹ of this parallax from eight plates; this showed that Professor Barnard's inference was correct and that the parallax is about one-quarter of a second. Professor Barnard's work confirmed this large value, and the parallax has also been investi-

¹ This preliminary work is entirely superseded by the present paper, where the same plates are definitively discussed in connection with others secured later.

gated by Professor Russell. The three results are very accordant, so that this system is not only included among the ten that are at present known to be nearest us, but is also one of an even shorter list whose distances are known with the least percentage of error.

TABLE I
PLATES OF *Krüger 60*

No.	Date	Hour Angle	Observers	Quality of Images	Remarks
45....	1903 July 12	-1 ^h .4	S, Su, S	Poor	Star (21) lacking on second and third exposures
49....	July 19	-1.7	S, Su, S	Fair	Second exposure poor
64....	Aug. 3	-0.5	S, Su, S	Fair	
171A....	Nov. 26	+1.2	S, Su, S	Good	Telescope East
182....	Dec. 6	+1.8	S, S, S	Fair	Telescope East
362....	1904 June 12	-1.9	S, Su	Fair	
373....	June 19	-1.7	S, Su, S	Fair	
378....	July 10	-1.5	S, Su, S	Fair	
382....	July 16	-1.2	S, Su, S	Good	
389....	July 17	-1.5	S, Su, S	Good	
448....	Sept. 4	-0.6	S, Su, S	Good	
459....	Sept. 11	-1.0	S, Su, S	Good	
511....	Oct. 30	-0.3	S, Su, S	Good	
712....	1905 July 22	-1.0	F, Su, F	Good	
717....	July 23	-1.0	F, Su, F	Good	
722....	July 25	-0.3	F, F	Good	
797....	Oct. 3	-0.9	Su, J, Su	Fair	
807....	Oct. 7	-0.2	Su, J, Su	Good	
850....	Nov. 12	-0.2	Su, J, Su	Fair	

COMPARISON STARS

No.	DIAMETER	X (longitude)	Y (latitude)	DEPENDENCE	
				Computed	Adopted
13.....	1.06	-188	- 97	+ .280	+ .285
15.....	1.18	-122	+136	+ .076	+ .08
21.....	0.71	+ 53	- 23	+ .289	+ .285
30.....	1.53	+257	- 16	+ .345	+ .35
Parallax star.	1.02	+ 40.4	- 29.9		

There is another good comparison star, numbered 22, at $X = +39$, $Y = +213$, but the dependence comes out small ($+0.017$) and it was therefore not used.

TABLE 2
REDUCTIONS IN RIGHT ASCENSION FOR *Krüger 60*

Plate	Solution (m)	Weight (p)	Parallax Factor (P)	Time in Days (t)	Residual (s)	$\sqrt{p \cdot s}$ in Arc
45.....	0.930	0.4	+0.662	-392	- .005	-.01
49.....	0.912	0.8	+0.579	-385	- 9	-.02
64.....	0.884	0.8	+0.331	-367	+ 3	+.01
171A.....	0.665	1.0	-0.920	-255	+ 3	+.01
182.....	0.648	0.6	-0.904	-245	- 7	-.01
362.....	0.680	0.6	+0.901	- 56	+ 17	+.03
373.....	0.656	0.5	+0.862	- 49	+ 3	+.01
378.....	0.598	0.8	+0.676	- 28	- 19	-.05
382.....	0.619	0.9	+0.606	- 22	+ 14	+.04
380.....	0.606	0.9	+0.594	- 21	+ 4	+.01
448.....	0.494	1.0	-0.132	+ 28	+ 5	+.01
459.....	0.474	1.0	-0.240	+ 35	+ 1	.00
511.....	0.368	0.9	-0.824	+ 84	- 5	-.01
712.....	0.261	0.9	+0.533	+349	- 11	-.03
717.....	0.271	0.9	+0.521	+350	+ 1	.00
722.....	0.268	0.6	+0.494	+352	+ 2	.00
797.....	0.091	0.7	-0.549	+422	- 12	-.03
807.....	0.082	0.9	-0.599	+426	- 13	-.03
850.....	0.059	0.7	-0.894	+462	+ 24	+.05

The normal equations are:

$$\begin{aligned}
 +6.166\pi - 4.212\mu + 0.706c &= +1.338 \\
 +113.334 + 7.015 &= -6.665 \\
 +14.900 &= +7.297
 \end{aligned}$$

These yield

$$\begin{aligned}
 c &= +0.527 \\
 \mu &= -0.0878 = -0''.234 \\
 \pi &= +0.0966 = +0''.257 \pm 0''.007
 \end{aligned}$$

Probable error corresponding to unit weight, $\pm 0.0067 = \pm 0''.018$

TABLE 3
REDUCTIONS IN DECLINATION FOR *Krüger 60*

Plate	Solution (<i>l</i>)	Weight (<i>p</i>)	Parallax Factor (<i>P</i>)	Time in Days (<i>t</i>)	Residual (<i>v</i>)	$\sqrt{p \cdot v}$ in Arc
45.....	0.526	0.2	+0.770	-392	+ .011	.00
49.....	0.510	0.8	+0.827	-385	- 9	-.02
64.....	0.523	0.8	+0.926	-367	+ 4	+.01
171A.....	0.368	1.0	-0.132	-255	0	.00
182.....	0.360	0.6	-0.200	-245	+ 11	+.02
362.....	0.318	0.6	+0.422	- 50	- 2	.00
373.....	0.319	0.5	+0.518	- 49	- 5	-.01
378.....	0.347	0.8	+0.758	- 28	+ 11	+.03
382.....	0.340	0.9	+0.811	- 22	+ 3	+.01
389.....	0.347	0.9	+0.819	- 21	+ 10	+.03
448.....	0.318	1.0	+0.900	+ 28	- 2	-.01
459.....	0.301	1.0	+0.861	+ 35	- 13	-.03
511.....	0.227	0.9	+0.289	+ 84	- 11	-.03
712.....	0.161	0.9	+0.853	+349	+ 4	+.01
717.....	0.153	0.9	+0.861	+350	- 5	-.01
722.....	0.151	0.6	+0.874	+352	- 7	-.01
797.....	0.123	0.7	+0.662	+422	+ 19	+.04
807.....	0.102	0.9	+0.614	+426	+ 4	+.01
850.....	0.024	0.7	+0.087	+462	- 9	-.02

The normal equations are:

$$\begin{aligned}
 +7.373\pi + 6.735\mu + 9.001c &= +2.612 \\
 +110.261 + 7.799 &= -2.871 \\
 +14.700 &= +4.154
 \end{aligned}$$

These yield

$$\begin{aligned}
 c &= +0.254 \\
 \mu &= -0.0495 = -0''.132 \\
 \pi &= +0.0893 = +0''.238 \pm 0''.011
 \end{aligned}$$

Probable error corresponding to unit weight, $\pm 0.0054 = \pm 0''.014$

Combining these two values of the parallax in accordance with their probable errors we have as the definitive parallax of the system

$$+0''.252 \pm 0''.006$$

Plates 171A and 182 were secured with the telescope on the unusual side of the pier. A least-squares solution in right ascension without these plates yields:

$$\begin{aligned}c &= +0.526 \\ \mu &= -0.0878 = -0''.233 \\ \pi &= +0.0968 = +0''.257 \pm 0''.010\end{aligned}$$

Probable error corresponding to unit weight, $\pm 0''.019$

A similar solution in declination gives

$$\begin{aligned}c &= +0.246 \\ \mu &= -0.0490 = -0''.130 \\ \pi &= +0.1003 = +0''.267 \pm 0''.018\end{aligned}$$

Probable error corresponding to unit weight, $\pm 0''.014$

The mean by weight of these two values of the parallax is $+0''.259 \pm 0''.009$, which differs by $0''.007$ from that which results from the use of all the plates. The original mean is allowed to stand as the definitive value.

Professor Barnard has obtained $+0''.249 \pm 0''.010$ for this parallax from an extensive series of measures with the 40-inch micrometer. Professor Russell has recently derived $+0''.258 \pm 0''.013$ from measures of plates secured at Cambridge, England.

Lalande 46650 ($23^h 44^m, +1^\circ 52'$)

This 9th-magnitude star has a proper motion of $1''.4$ per annum. Thirteen plates were secured as described in Table 1. There is considerable displacement in declination and the plates were accordingly measured in this direction (as well as in right ascension) but the parallax from this co-ordinate proved to have little weight.

TABLE I
PLATES OF *Lalande 46650*

No.	Date	Hour Angle	Observers	Quality of Images	Remarks
51....	1903 July 19	-1 ^h 8	S, Su, S	Poor	
60....	Aug. 2	-1.3	S, Su, S	Fair	Second exposure poor
70....	Aug. 11	-0.5	S, Su, S	Fair	Second exposure poor
399....	1904 July 24	-0.9	S, Su, S	Good	
432....	Aug. 25	-0.6	S, Su, S	Good	
498....	Oct. 16	0.0	S, (Su, S)	Fair	Second and third exposures coincide
513....	Oct. 30	-0.4	S, Su, S	Good	
715....	1905 July 22	-0.2	F, Su, F	Fair	First exposure poor
720....	July 23	-0.6	Su, F	Fair	
724....	July 25	-0.2	F, F		First exposure fair, second good
812....	Oct. 7	+1.0	Su, J, Su	Good	
821....	Oct. 8	+1.0	Su, J, Su	Fair	Second exposure good
852....	Nov. 12	-0.5	Su, J, Su	Poor	

COMPARISON STARS

No.	DIAMETER	X (right ascension)	Y (declination)	DEPENDENCE	
				Computed	Adopted
3.....	0.70	-363	+102	+ .647	+ .645 = +1.00 ÷ 1.55
9.....	0.63	+ 97	+158	- .038	- .032 = -0.05 ÷ 1.55
11.....	0.74	+266	-260	+ .390	+ .389 = +0.60 ÷ 1.55
Parallax star....	1.25	-134	- 42		

Plates 432, 498, and 513 were measured by both Miss Ware and the writer, the others by Miss Ware alone. The accordance between the two sets of measures for these three plates is such, that if only Miss Ware's measures had been used for them (as for the other ten plates) the effect upon the parallaxes deduced from either right ascensions or declinations would have been practically nil.

TABLE 2
REDUCTIONS IN RIGHT ASCENSION FOR *Lalande 46650*

Plate	Solution (<i>m</i>)	Weight (<i>p</i>)	Parallax Factor (<i>P</i>)	Time in Days (<i>t</i>)	Residual (<i>v</i>)	$\sqrt{p \cdot v}$ in Arc
51.....	0.087	0.4	+0.801	-385	-.018	-.03
60.....	0.099	0.6	+0.668	-371	- 11	-.02
70.....	0.141	0.6	+0.562	-362	+ 28	+.06
399.....	0.470	0.9	+0.751	- 14	- 7	-.02
432.....	0.494	1.0	+0.364	+ 18	+ 9	+.02
498.....	0.481	0.6	-0.426	+ 70	- 9	-.02
513.....	0.490	1.0	-0.606	+ 84	- 3	-.01
715.....	0.846	0.6	+0.771	+349	+ 2	.00
720.....	0.849	0.5	+0.763	+350	+ 4	+.01
724.....	0.845	0.5	+0.744	+352	- 1	.00
812.....	0.841	0.9	-0.293	+426	- 16	-.04
821.....	0.875	0.8	-0.308	+427	+ 18	+.04
852.....	0.876	0.4	-0.739	+462	+ 9	+.02

The normal equations are:

$$\begin{aligned}
 +3.126\pi - 3.915\mu + 1.647c &= +0.526 \\
 +82.185 + 10.078 &= +12.561 \\
 +8.800 &= +5.036
 \end{aligned}$$

These yield

$$\begin{aligned}
 c &= +0.445 \\
 \mu &= +0.1010 = +0''.269 \\
 \pi &= +0.0606 = +0''.161 \pm 0''.014
 \end{aligned}$$

Probable error corresponding to unit weight, $\pm 0.0079 = \pm 0''.021$

TABLE 3
REDUCTIONS IN DECLINATION FOR *Lalande 46650*

Plate	Solution (<i>l</i>)	Weight (<i>p</i>)	Parallax Factor (<i>P</i>)	Time in Days (<i>t</i>)	Residual (<i>v</i>)	$\sqrt{p \cdot v}$ in Arc
51.....	0.924	0.4	+0.379	-485	-.023	-.04
60.....	0.923	0.6	+0.333	-471	-8	-.02
399.....	0.590	0.9	+0.363	-114	+13	+.03
432.....	0.542	1.0	+0.215	-82	+2	+.01
498.....	0.481	0.6	-0.129	-30	+5	+.01
513.....	0.468	1.0	-0.215	-16	+9	+.02
715.....	0.221	0.6	+0.369	+249	+4	+.01
720.....	0.239	0.5	+0.366	+250	+23	+.04
724.....	0.184	0.5	+0.360	+252	-30	-.06
812.....	0.119	0.9	-0.067	+326	-6	-.02
821.....	0.119	0.8	-0.074	+327	-5	-.01
852.....	0.073	0.4	-0.283	+362	-9	-.02

The normal equations are:

$$\begin{aligned}
 +0.600\pi - 1.507\mu + 0.954c &= +0.601 \\
 +58.022 + 4.050 &= -3.988 \\
 +8.200 &= +3.329
 \end{aligned}$$

These yield

$$\begin{aligned}
 c &= +0.451 \\
 \mu &= -0.0993 = -0''.264 \\
 \pi &= +0.0358 = +0''.095 \pm 0''.033
 \end{aligned}$$

Probable error corresponding to unit weight, $\pm 0.0081 = \pm 0''.022$

The two values of the parallax differ somewhat more than we should expect from their probable errors. Combining them in accordance with these errors we obtain for our definitive result:

$$+0''.151 \pm 0''.013$$

Other determinations of this parallax are:

Flint (transit circle).....	+0''.23	$\pm 0''.092$
Elkin and Smith (heliometer).....	+ .185	16
Russell (photography).....	+ .211	15

ALLEGHENY OBSERVATORY

April 1911

[To be concluded]

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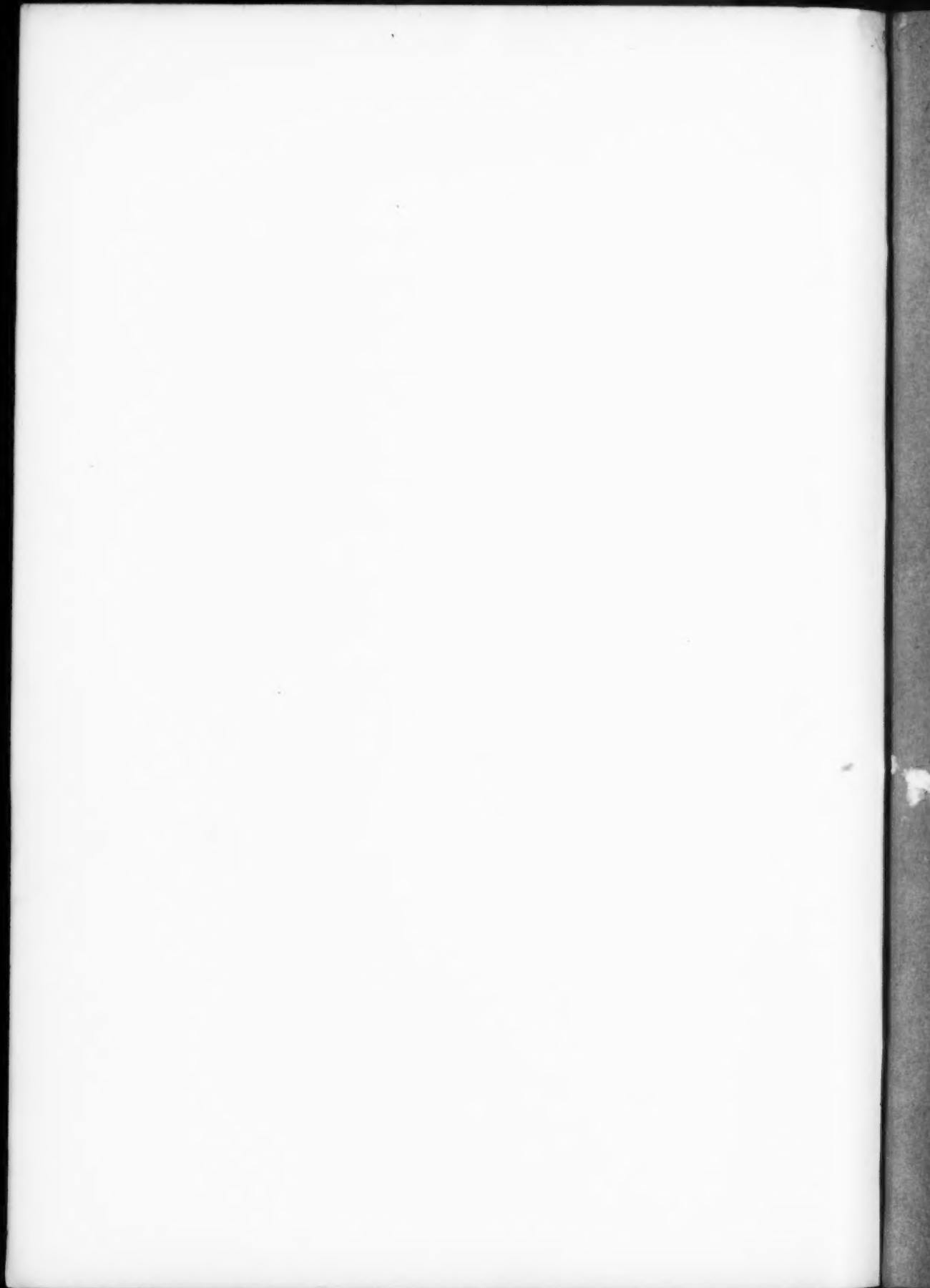
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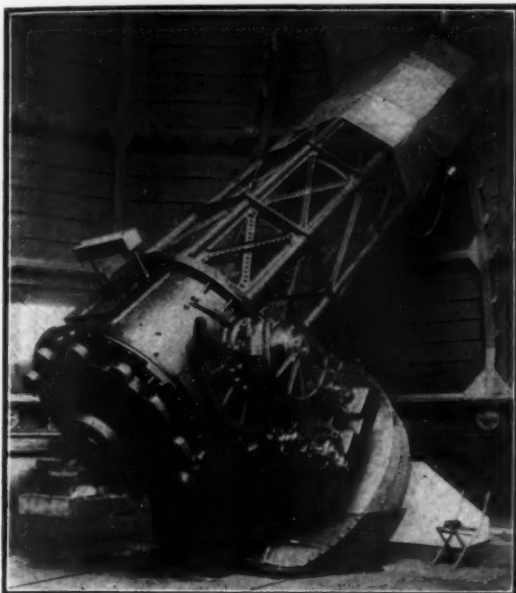
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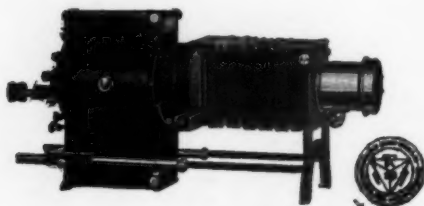


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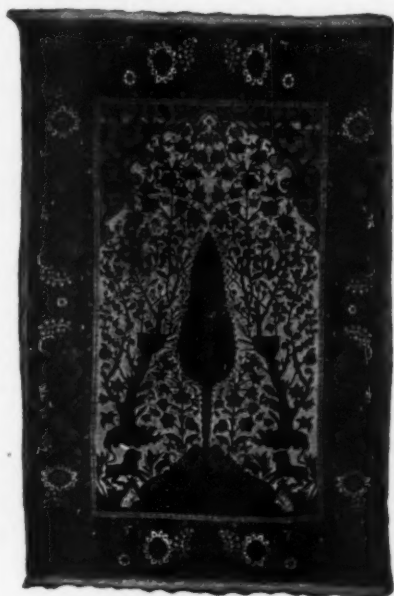
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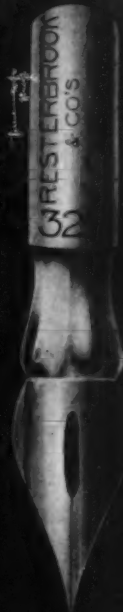
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